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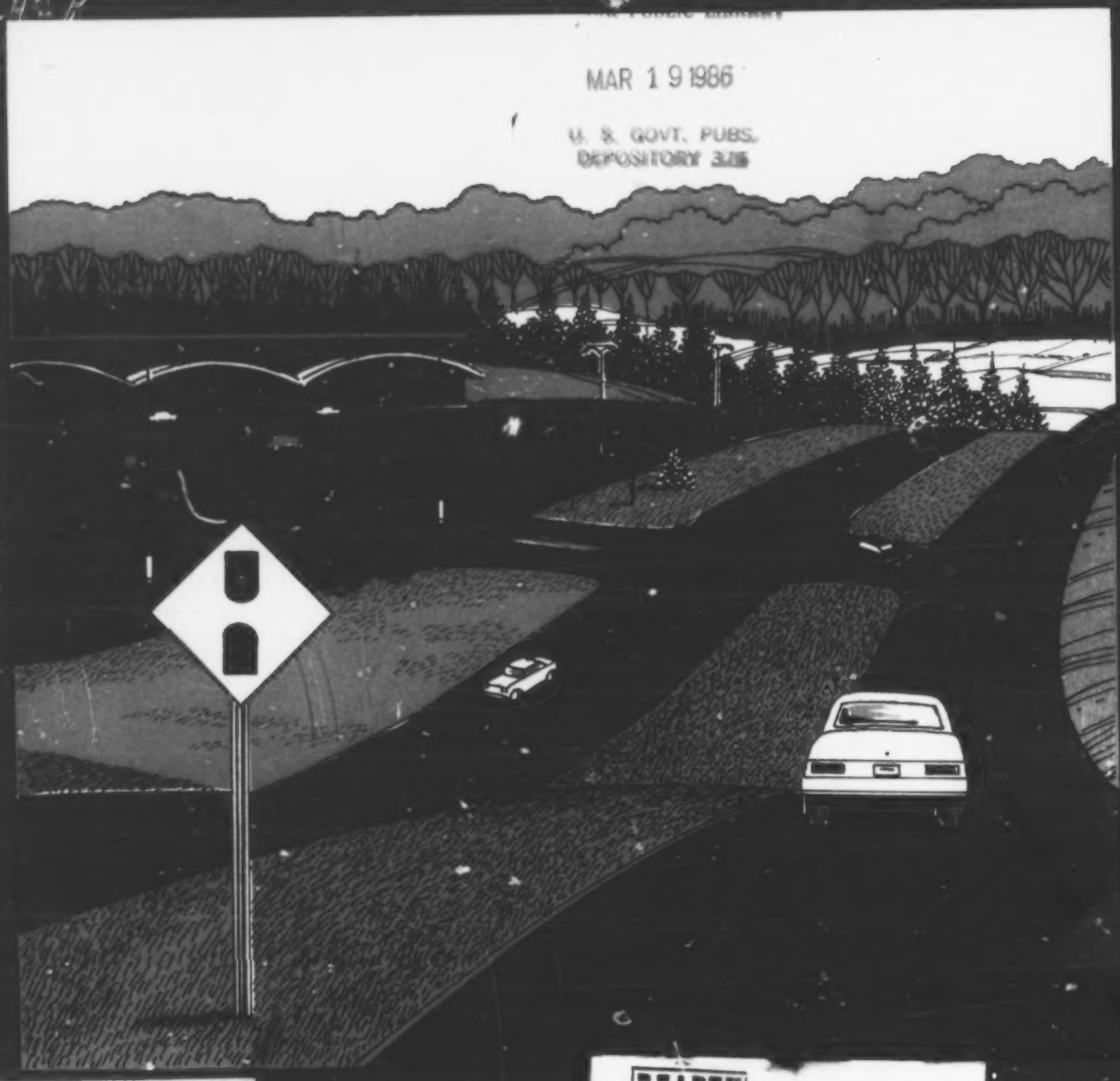

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COVER: An advanced warning median crossover symbolic sign showing two median crossover noses did well in legibility and understanding tests, was least confused with other signs tested, and was most preferred by subjects in a study conducted at the Turner-Fairbank Highway Research Center in McLean, Virginia.

U.S. Department of Transportation
Elizabeth Hanford Dole, *Secretary*

Federal Highway Administration
R.A. Barnhart, *Administrator*

U.S. Department of Transportation
Federal Highway Administration
Washington, DC 20590

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Investigation of Warning Signs for Median Crossovers

by

Gillian M. Worsey, Charles E. Dare,
Richard N. Schwab, and Samuel C. Tignor

This article describes the results of a study of advanced warning median crossover signs that were tested in a laboratory for legibility, understanding, recognition, and preference. The study indicated that the most appropriate word message sign would be MEDIAN CROSSOVER. Such a sign was not actually tested but the subjects understood a MEDIAN OPENING sign the best, and the majority of subjects thought that "crossover" was the word that best conveyed the intended meaning. Legibility of the symbolic signs, however, was much greater than for the word messages.

The symbolic sign found to be the best out of those tested was one showing two crossover noses. This sign did well in legibility and understanding tests, was least often confused with other signs, was the sign most preferred by the subjects, and also was the simplest of the warning sign symbolic designs.

Introduction

Median openings often are used on divided arterials and other nonfreeway highways between intersections to accommodate minor turning movements into driveways and U-turns to assist maintenance operations, policing, and repair service to stalled vehicles. About 35 percent of the accidents occurring between intersections on four-lane highways involve median openings. (*1*)[1] The largest percentage of these accidents involves vehicles attempting to cross four lanes through a median opening (table 1).

The Manual on Uniform Traffic Control Devices (MUTCD) provides for the use of a median crossover sign (D13-1) but does not suggest nor identify an advanced, warning-type traffic control device for median crossovers. Roadway delineators used to identify horizontal alignment and hazards adjacent to the roadway are also commonly used at median crossovers.

In response to a proposal by the Virginia Highway and Transportation Research Council (VHTRC) that a research study investigate the effectiveness of traffic control devices at median crossovers, the Federal Highway Administration (FHWA) conducted such a study last summer at its Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia. This article describes the investigation of the effectiveness of various advanced warning signs and delineators at median openings.

Study Methodology

Test Signs

Sixteen candidate advance warning median crossover signs were identified from a literature review and survey of current State practices. To keep testing time to approximately 1 hour, only seven of these signs were selected for laboratory testing of legibility, understanding, and driver recognition.

[1]Italic numbers in parentheses identify references on page 121.

Table 1.—Frequency of median opening accidents by accident type (1)

Accident type	Accidents	
	Number	Percent
Hit while attempting to cross four lanes	899	39
Hit from front while turning through median opening	589	25
Hit from rear while turning from outside lane	445	19
Hit from rear while turning through median opening	297	13
Hit from rear after turning through median opening	88	4

The seven candidate signs included five symbolic and two word signs (fig. 1). The word sign CROSSOVER was used because it is the wording on the sign included in the MUTCD, and the word sign MEDIAN OPENING was used because it included the word "median."

Five of the signs tested were yellow diamond warning signs. The two permissive signs included the sign from Virginia that led to the original study request and a Permissive U-Turn sign, both of which had green backgrounds to denote permissive signs.

The seven signs were composed on a computer graphics system as were three other signs used as distractors. Ten other MUTCD signs composed on the computer graphics system as part of other FHWA studies also were used as distractors, making a total of 20 signs for subject viewing. The signs were superimposed onto a digitized photograph of a median crossover so that the crossover signs were in an appropriate environment with associated visual cues. Slides and prints then were made of the superimposed signs (fig. 2).

The slides were rear-projected onto a translucent screen. The size of the projected image of the signs, 2 3/8 in (60.3 mm) from point to point of the yellow diamond, was chosen so that subjects with the best eyesight could not recognize familiar signs at the farthest distances from the image (110 ft [33.5 m]). A long advance projector control cord allowed the slides to be advanced from the 110-ft (33.5-m) distance.

The testing took place in a tunnel approximately 12 ft (3.7 m) wide by 12 ft (3.7 m) high by 120 ft (36.6 m) long at the TFHRC. The slide projector and screen were at one end of the tunnel.

Subjects

Thirty paid subjects participated in the testing—five males and five females from each of three age groups (16–29 years, 30–49 years, and 50 years and over). The mean age was 40.5 years (table 2). All subjects had their vision tested to ensure corrected visual acuity of 20/33 or better. The average visual acuity was 20/20. The 16 subjects who wore corrective lenses for driving also wore them during the laboratory testing. All subjects had correct color vision.

Testing procedure

The study addressed the subjects' understanding and recognition of the signs tested as well as the legibility of the signs. Legibility, or the clarity of the sign, involves letter size, width, and spacing; color; and contrast. Understanding relates to the subject's ability to correctly interpret the meaning of the sign. In this study, the initial measure was the subject's uncued understanding; before seeing the seven candidate signs, the subjects were not given any information on the meaning or purpose of the signs. After the subjects had been initially tested with all of the candidate signs, the signs' meanings were explained. This subsequent sign understanding in further testing was known as cued understanding. Recognition relates to the subject's cued understanding and ability to identify a sign correctly in a short period of time.

Legibility and understanding

Each subject was briefed on how the testing would be conducted. After any questions the subject had were answered, the first slide was projected on the screen. The subject walked toward the projected sign until he/she could identify any feature on the sign. The feature and the distance at which it was identified were recorded until all the major features of each sign had been identified.

The subjects also were instructed to give the uncued meaning of the sign as soon as they thought they knew it. If the meaning they gave was incorrect, they were instructed to try again. To prevent long viewing times, the subjects were encouraged to guess, if necessary, the meaning of the sign.

When the subject had identified all of the features of the sign, he/she walked back to the beginning of the tunnel, the next slide was presented, and the procedure was repeated. This process was repeated until the subject had seen all 20 slides. The slides were presented randomly (a different order for each subject) with the stipulation that the first two signs were not candidate crossover signs. In this way, the subjects, without being aware of it, practiced the procedure with a distractor sign.

Recognition

After the subjects had completed the sign legibility and understanding testing, the intended meaning of the crossover signs was explained and the subjects were given prints of the seven candidate median crossover signs to become familiar with them.

Table 2.—Mean ages of subject groups

Sex	Age in years			
	16–29	30–49	50 and over	Mean
Male	21.2	38.8	59.8	39.93
Female	24.0	42.0	57.4	41.13
Mean	22.6	40.4	58.6	40.50

CROSSOVER
(black on yellow)

Crossover Arrows
(black on yellow)

Permissive Crossover—Virginia
(white on green)

MEDIAN OPENING
(black on yellow)

Permissive U-Turn (black on
white, green background)

Crossover Nose
(black on yellow)

Crossover Nose plus Arrows
(black on yellow)

Figure 1.—Candidate median crossover signs.

Figure 2.—Crossover sign superimposed onto digitized photograph of a median crossover.

The subjects were shown the slides again, this time in a different random order. The subject walked toward the projected sign until he/she could identify it. Again to prevent long viewing times and to maximize confusion, the subjects were encouraged to guess the signs' meanings as far as possible from the screen. Any confusion and the distance at which it occurred were recorded as was the distance at which the subject correctly identified each sign. When each sign had been identified correctly, the subject walked back to the beginning of the tunnel, the next slide was presented, and the procedure was repeated until each subject had seen all 20 slides.

Preference

Although the three basic study areas were legibility, understanding, and recognition, a fourth area of interest was subject preference for the candidate signs. In the final part of the testing, the subjects were instructed to arrange prints of the seven crossover signs in order of preference. The rank of each sign then was recorded. The subjects also were asked several questions concerning their thoughts on the use and meaning of median crossover signs.

Results

Legibility

Table 3 summarizes statistics for the identification of features data. The mean distances reported here in feet are a relative measure of legibility from this laboratory test and not the distances at which drivers would be able to read the signs in a real driving situation.

Sign shape was identified for all but the Virginia sign at a mean of approximately 100 ft (30.5 m). The shape of the Virginia sign could not be identified until considerably closer—a mean of approximately 63 ft (19.2 m). Statistical analysis showed mean distance for the Virginia sign was significantly different. Sign color could be identified at a mean of approximately 100 ft (30.5 m) or more for all of the signs, and the mean distances for each sign were not significantly different.

The mean distance at which the color of the symbol or letters could be seen was between 70 and 90 ft (21.3 and 27.4 m) for all but the Virginia sign and the Permissive U-Turn sign, which had color identification distances of approximately 57 and 55 ft (17.4 and 16.8 m), respectively. Statistical analysis showed these two mean distances were significantly different.

The presence of a symbol could be seen at a mean of approximately 80 to 90 ft (24.4 to 27.4 m) for the Crossover Nose, Crossover Nose plus Arrows, and Crossover Arrows signs; for the Permissive U-Turn sign and the Virginia sign, the means were shorter, approximately 66 and 52 ft (20.1 and 15.8 m), respectively. Letters on word signs could not be seen until somewhat closer—a mean of approximately 54 ft (16.5 m) for the MEDIAN OPENING sign and a mean of approximately 48 ft (14.6 m) for the CROSSOVER sign. Statistical analysis again showed that these mean distances were significantly different.

The individual pictographic elements on each sign were identified at varying distances; the most obvious result was that the word signs could be read only at very short distances—a mean of approximately 12 ft (3.7 m) for the CROSSOVER sign and a mean of approximately 11 ft (3.4 m) for the MEDIAN OPENING sign. Statistical analysis of the distances at which the smallest pictographic element could be identified showed that these mean distances were significantly different.

The directional information conveyed by the symbol on the Crossover Arrows sign could be seen at a mean of approximately 50 ft (15.2 m) compared with a mean of approximately 35 ft (10.7 m) for the presence of the crossover nose symbol on the Crossover Nose, Crossover Nose plus Arrows, and Virginia signs. The symbol on the Permissive U-Turn sign was seen the least well, at a mean of approximately 25 ft (7.6 m).

No significant relationship was found between the identification distance and the size of the largest dimension of the symbol or the largest dimension of individual pictographic elements. No significant relationships were found between identification distances and biographic variables such as age, sex, weekly mileage driven, accidents and violations in the past 5 years, and wearing corrective lenses. As might be expected, subjects with the best visual acuity had longer identification distances for all of the signs but the Permissive U-Turn sign.

Table 3.—Means and standard deviations of legibility distances (ft)

Feature		Sign						
		CROSSOVER	MEDIAN OPENING	Permissive Crossover—Virginia	Crossover Nose	Crossover Nose plus Arrows	Crossover Arrows	Permissive U-Turn
Shape of sign	M	99.90	106.67	62.77	101.96	103.63	108.20	100.64
	SD	15.35	10.18	29.38	12.91	12.50	5.64	19.73
	N[1]	30	30	26	28	30	30	28
Color of sign	M	106.30	107.87	99.03	105.67	107.40	107.80	100.27
	SD	7.47	7.01	20.85	9.91	6.99	5.93	19.75
	N	30	30	30	30	30	30	30
Color of symbol or letters	M	74.96	70.95	57.48	78.82	84.04	89.16	54.92
	SD	26.29	25.20	27.54	24.84	22.15	22.09	31.58
	N	23	22	29	28	27	25	26
Presence of symbol or letters	M	48.10	53.93	51.75	82.54	84.86	89.56	65.88
	SD	24.59	19.42	20.24	21.53	21.65	20.97	28.22
	N	29	30	8	26	29	25	25
Presence of median nose	M			34.03	36.20	34.60		26.43
	SD			12.61	10.88	13.42		11.98
	N			30	30	30		30
Road pattern	M					34.43	52.23	24.97
	SD					11.71	16.59	6.69
	N					30	30	30
Crossover movement	M						48.37	24.73
	SD						11.77	7.08
	N						30	30
Read legend	M	12.27	11.40					
	SD	3.50	3.41					
	N	30	30					

[1] Sample sizes (N) differ because not all subjects mentioned all features.

1 ft = 0.305 m

Legend
M = Mean
SD = Standard deviation
N = Number of subjects

A breakdown of the data according to sex showed that the females identified the shapes and colors of the signs and the presence and colors of the symbols at slightly longer distances, whereas the males identified the details on the signs at longer distances. However, statistical analysis did not show any significant effects of sex on the legibility distances. A breakdown of the data according to age did not show any consistent differences.

Uncued understanding

The subjects were encouraged to guess the meaning of the signs as soon as possible. Their answers were coded according to whether they made an incorrect guess before a correct one or could not guess the meaning (table 4). No consistent patterns of replies were found when the data were broken down according to age or sex.

The sign that conveyed the meaning most successfully was the MEDIAN OPENING sign for which all of the subjects gave the correct meaning, 27 of the subjects without a wrong guess first. Least understandable was the Permissive U-Turn sign for which only 15 subjects gave the correct meaning and only 9 of these subjects

Table 4.—Frequencies of correctness of answer by kind of sign

Kind of answer	Sign						
	CROSSOVER	MEDIAN OPENING	Permissive Crossover—Virginia	Crossover Nose	Crossover Nose plus Arrows	Crossover Arrows	Permissive U-Turn
Correct answer first time	16	27	13	18	15	13	9
Partially correct answer before correct answer or Incorrect guess before correct answer	10	3	4	5	8	11	6
Incorrect guess and no correct answer or Don't know	4	0	13	7	7	6	15

without a wrong guess first. The Virginia sign also caused problems, with 17 subjects giving a wrong guess first, and 13 of these subjects never guessing the correct meaning.

The signs were confused or misinterpreted nearly 100 times (table 5). The Crossover Arrows sign was confused most often, mainly with "hospital" or "H." The Crossover Nose plus Arrows sign also was confused numerous times, mainly with "divided highway" or "two-way traffic." The CROSSOVER sign was confused an equal number of times, mainly with "crossroads," "bridge or overpass," and "construction." Confusion of this word sign occurred probably from misreading rather than from not understanding the meaning of the sign. Some of the more obscure misinterpretations of the signs included "mountains," "football," "tunnel," "jogging," and "use seatbelts."

Table 6 shows the frequency of misinterpretations based on age and sex. The 30-49 years age group misinterpreted the signs more often than did the other age groups. Females 16-29 years old misinterpreted the signs more often than did males of the same age group, but this could be because of a greater willingness to guess rather than because of a greater difficulty in understanding the signs. No pattern was found in the kinds of misinterpretations for each sign according to age or sex.

The mean distances at which subjects understood the meanings of the signs are shown in figure 3. The word signs were understood at much shorter distances than the symbolic signs because the subjects had to be able to read the signs before they could understand them. The Crossover Arrows sign was understood at the farthest distance and also by the most subjects; however, this sign also caused the most confusion before a correct answer was given. Statistical analysis of the distances at which subjects understood the signs showed that the distances were significantly different.

No significant relationships were found between understanding distances and biographic variables such as age, sex, weekly mileage driven, accidents and violations in the past 5 years, visual acuity, and wearing corrective lenses. A breakdown of the data according to age and sex did not show any consistent differences.

Recognition

The recognition tests were conducted after the subjects were told the meaning of the signs. Figure 4 shows the mean distances at which the subjects recognized the signs. The Virginia sign was recognized at by far the greatest mean distance because of its distinctive color and shape, followed by the Permissive U-Turn sign. The word signs again were recognized at the closest mean distances. Statistical analysis of the mean recognition distances showed that the distances were significantly different.

Table 7 shows the frequency of confusions for each sign. The Crossover Nose sign was the only sign not recognized by all of the subjects. The total number of confusions was only 20; 8 of these involved the Crossover Nose plus Arrows sign, which mainly was confused with "divided highway." The Crossover Arrows sign was confused five times.

No significant relationships were found between recognition distances and biographic variables such as sex, weekly mileage driven, accidents and violations in the past 5 years, and wearing corrective lenses. However, age was negatively related to recognition distances for the MEDIAN OPENING, Crossover Nose, Crossover Nose plus Arrows, and Crossover Arrows signs; younger subjects found these signs easier to recognize than did older subjects. The recognition distances for younger subjects also were longer than for older subjects for all of the symbolic signs but not for the word signs. Mean recognition distances were longer for each younger age group; however, statistical analysis did not show any significant effects of age on the recognition distances.

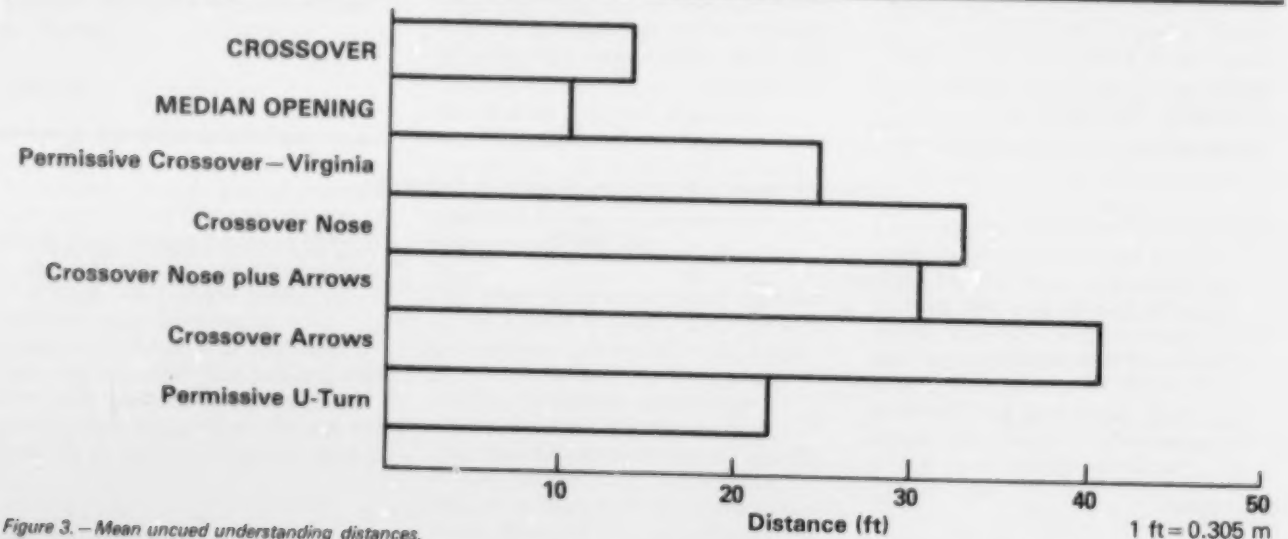


Figure 3.—Mean uncued understanding distances.

Table 5.—Frequencies of misinterpretations by kind of sign

	Sign						
	CROSSOVER	MEDIAN OPENING	Permissive Crossover—Virginia	Crossover Nose	Crossover Nose plus Arrows	Crossover Arrows	Permissive U-Turn
Misinterpretations	18	5	10	11	18	23	13
Subjects who could not guess the meaning at all	0	0	8	3	2	0	10

Table 6.—Frequencies of misinterpretations by age and sex

	Age in years			
Sex	16-29	30-49	50 and over	Total
Male	11	21	14	46
Female	19	19	14	52
Total	30	40	28	98

A breakdown of the data according to sex did not show any consistent differences in the mean recognition distances; however, females confused the signs with other meanings more often than did males.

Preference

Figure 5 shows the mean preference ranking subjects gave to the signs. They ranked the sign that they thought best conveyed the message of a median crossover as number 1 and the sign that they thought least conveyed the message as number 7. The most obvious conclusion from figure 5 is that the Permissive U-Turn sign was the least preferred, with an average rank of 6. The Crossover Nose and Crossover Nose plus Arrows signs were the most preferred, followed by the two word signs, the Crossover Arrows sign, and the Virginia sign. Statistical analysis indicated there was a significant difference among the mean preference ranks of the signs. A breakdown of the preference rank data according to age and sex showed the most agreement within the 16-29 year age group in ranking the signs, especially among the females.

Subjects' answers to general questions on median crossovers indicate a need exists that could be filled by the use of crossover signs. Twenty-two of the subjects (73 percent) thought public use of crossovers constitutes a hazard on divided highways, and 29 subjects (97 percent) thought that a sign would help them locate a crossover.

Subjects clearly were aware of the problems associated with crossovers. The most frequently mentioned hazard was slowing traffic in the fast lane, followed by traffic accelerating into the fast lane, turning traffic, and lane changes. One subject thought a crossover might lead to someone driving on the wrong side of the road. The possibility of rear-end collisions was mentioned by seven subjects, and broadside collisions by four subjects. Only two subjects did not associate any hazard with crossovers.

Subjects also were asked what effect a crossover sign would have on their driving. Twelve subjects said they would look for the sign if they wanted to locate a crossover, and two subjects said they would be able to change lanes or to signal when they saw the sign if they wanted to use a crossover. Fifteen of the subjects said they would look for slowing traffic if they saw a crossover sign, five said they would slow down, and four said they would change lanes. Only one subject said the sign would have no effect on his/her driving.

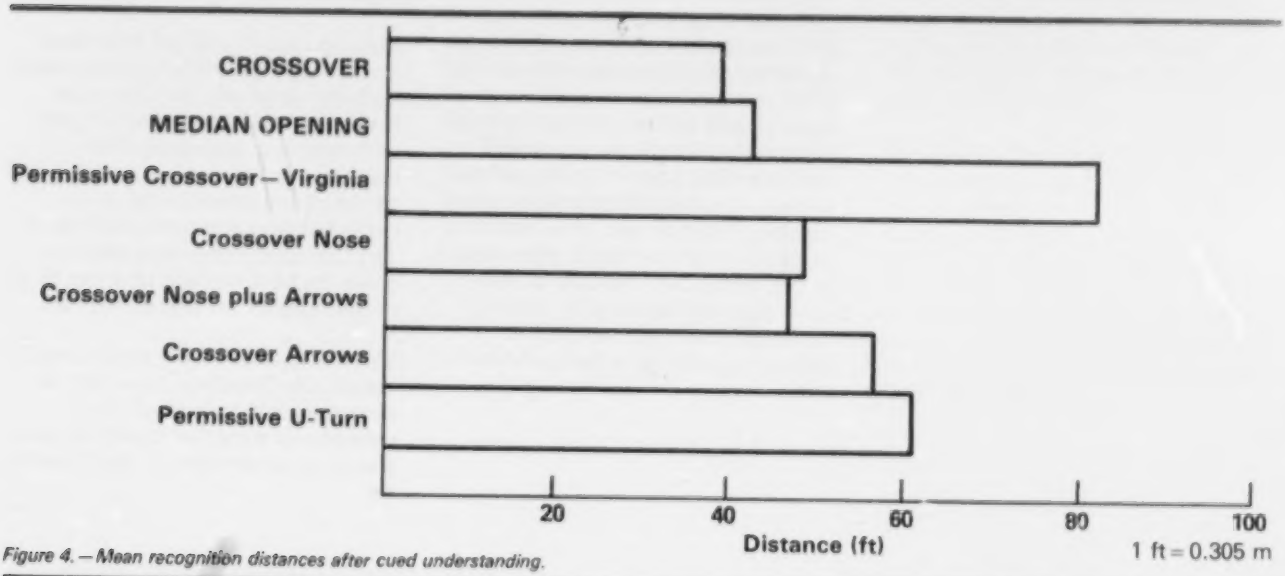


Figure 4.—Mean recognition distances after cued understanding.

Table 7.—Frequencies of confusions by kind of sign after cued understanding

	Sign						
	CROSSOVER	MEDIAN OPENING	Permissive Crossover—Virginia	Crossover Nose	Crossover Nose plus Arrows	Crossover Arrows	Permissive U-Turn
Confusions	2	2	0	2	8	5	1
Subjects who did not know the meaning	0	0	0	1	0	0	0

When asked whether "crossover," "crossing," or "opening" conveyed the intended meaning best, 20 subjects chose "crossover," 7 chose "opening," and 3 chose "crossing." Subjects also were asked if the addition of the word "median" would help clarify the meaning, and 24 subjects (80 percent) said that it would.

The most common reply to questions about the distance a sign should be located in front of the crossover was time to slow down and stop before the crossover. Two-thirds of the subjects gave distances of over 400 ft (122 m) when traveling at 55 mi/h (89 km/h). The American Association of State Highway and Transportation Officials stopping sight distances are 450 to 550 ft (137 to 168 m) at 55 mi/h (89 km/h) on wet pavements. Twenty-eight of the subjects (93 percent) thought that adding a distance plate beneath the sign would help them locate the crossover.

Conclusions

The majority of subjects in this study perceived crossovers as potentially hazardous locations and felt that signs indicating the presence of a median crossover would likely have a beneficial effect on their driving behavior.

Subjects also felt that the signs should not be placed closer than the stopping sight distance in front of a crossover or at a distance of 500 to 1,000 ft (152 to 305 m) on a 55 mi/h (89 km/h) highway.

The use of the word "median" in a word message sign is best understood by uncued subjects. Most of the subjects chose "crossover" rather than "crossing" or "opening" as best conveying the intended meaning. Therefore, it is recommended that if a word message sign is used, it should be MEDIAN CROSSOVER. The lettering in the word "crossover" would have to be small to fit on a standard diamond sign, or an oversized sign would have to be used.

The results of the legibility, understanding, and recognition distance sections of this study as well as results of other studies (2) clearly show that although word message signs usually can be understood once they are read, they are less legible than symbolic signs. The Crossover Arrows sign had the best mean legibility distances and understanding distances of the symbolic signs tested in this study; but it had by far the most misinterpretations by uncued subjects. It also was not highly ranked by subjects in the preference test.

Of the other symbolic signs, the Permissive U-Turn sign had low mean legibility distances and understanding distances and was least understood by the subjects. It was ranked last by the majority of subjects in the preference test. The significance of the green background to indicate a permissive sign was not understood at all.

The Virginia sign also had low mean legibility distances and was not well understood by uncued subjects. It was not highly ranked in the preference test but did very well in the recognition test, presumably because of its different color and shape. It was recognized at a far greater mean distance than any of the other signs and was the only sign not confused at all after the subjects had been cued to its meaning. Several subjects mentioned that if they had initially known the meaning of the sign, they thought this sign would be the best one to use. However, as the meaning of the sign was not at all obvious to the uncued subjects, it would require extensive education of drivers to make the sign a useful traffic engineering tool.

Although the Crossover Nose plus Arrows sign had slightly better mean legibility distances, the Crossover Nose sign had slightly better mean understanding and recognition distances and was misinterpreted and confused less often in the understanding and recognition tests. The Crossover Nose sign also was given the best average rank out of all of the signs in the preference test.

Therefore, of all of the symbol signs tested, the Crossover Nose sign is recommended to indicate the presence of a median crossover and also is recommended for field evaluation.

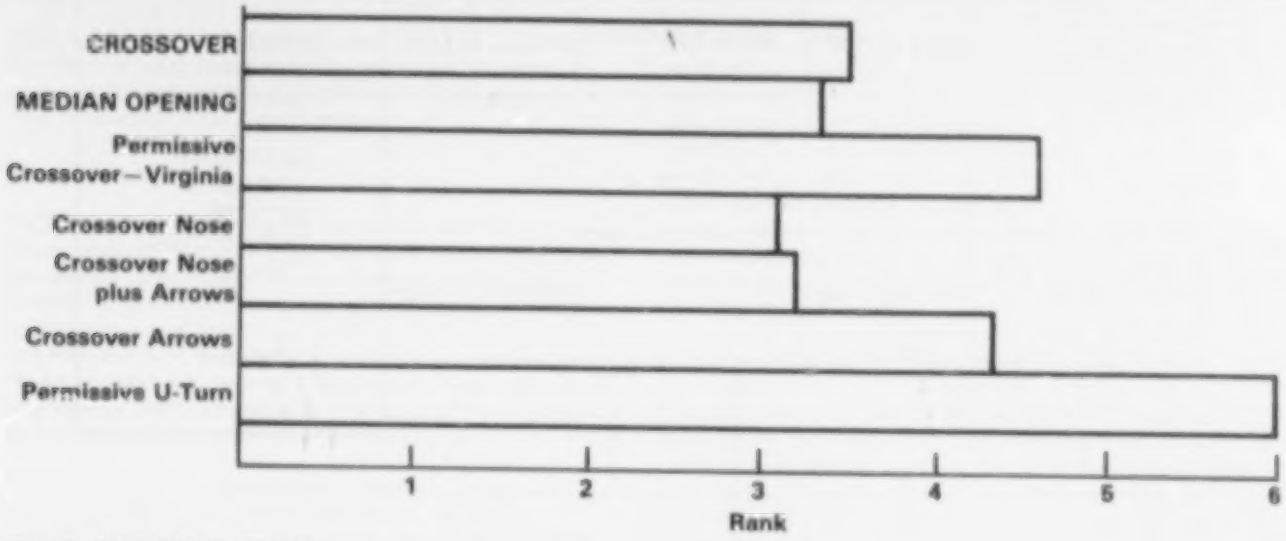


Figure 5.—Mean preference rankings.

REFERENCES

(1) P.D. Cribbins, J.M. Avey, and J.K. Donaldson, "Effects of Selected Roadway and Operational Characteristics on Accidents on Multi-Lane Highways," Highway Research Board Record 188, *Highway Research Board*, Washington, DC, 1967.

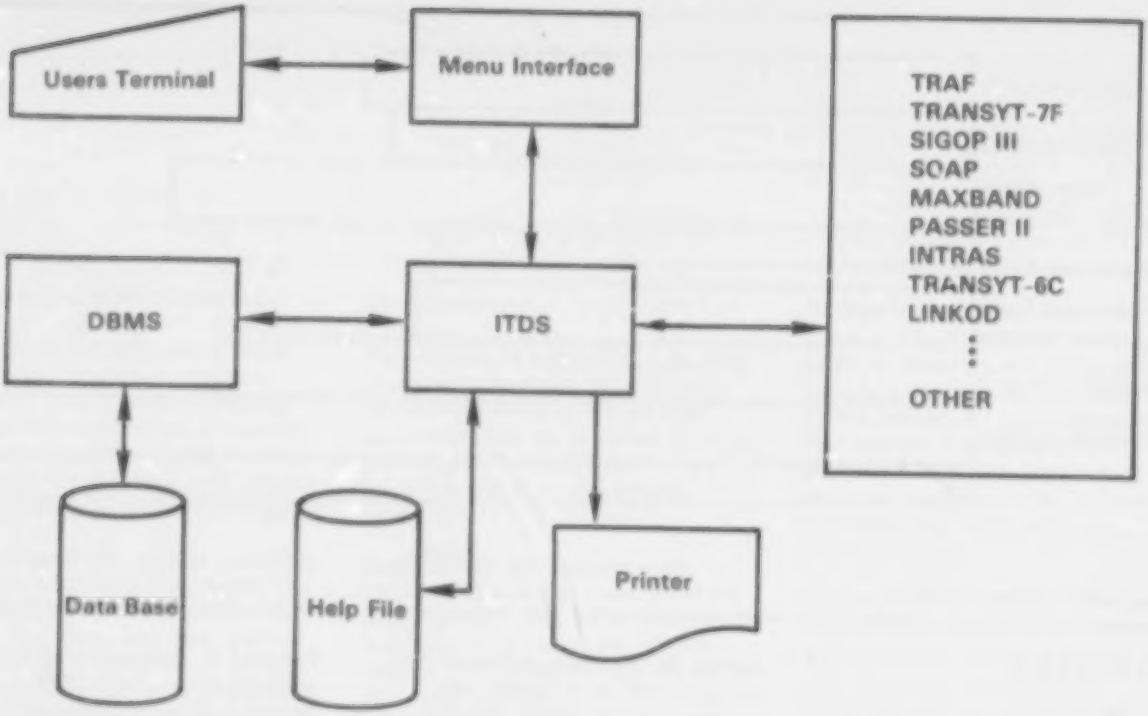
(2) R.J. Jacobs, A.W. Johnston, and B.L. Cole, "The Visibility of Alphabetic and Symbolic Traffic Signs," Report 5(7), *Australian Road Research*, 1975, pp. 68-87.

Gillian M. Worsey performed this study in 1985 as a student participating in the FHWA Research Fellowship Program. Ms. Worsey is a Ph.D. candidate at the University of Missouri-Rolla. As part of her dissertation she also will perform a similar study in Rolla to determine if there are any regional differences in the results reported in this article.

Charles E. Dare is the Director of the FHWA-sponsored Transportation Technical Assistance Office at the University of Missouri-Rolla. He also serves as faculty advisor to the Institute of Transportation Engineers Student Chapter at UMR and is in charge of the transportation area in the Civil Engineering Department. Dr. Dare is active in the Transportation Research Board Committee on Traffic Control Devices and the Committee on Transportation Planning Needs and Requirements for Small- and Medium-Sized Communities.

Richard N. Schwab is an electrical engineer in the Traffic Safety Research Division, Office of Safety and Traffic Operations Research and Development, Federal Highway Administration. He has been with FHWA since 1962 and is project manager for FCP Project 1P, "Night Visibility." His technical background is physiological optics and sensory capability of the human visual system. Mr. Schwab's work at FHWA has involved establishing the effects of adverse environmental conditions such as darkness, fog, snow, dust, and rain on traffic flow and highway safety and developing methods for overcoming these effects. Before joining FHWA, he was a graduate assistant on the staff of the Institute for Research in Vision at Ohio State University.

Samuel C. Tignor is Chief of the Traffic Safety Research Division, FHWA. He manages research pertaining to traffic signs, markings, and signals; highway operations; work zone safety; railroad-highway at-grade crossings; lighting; and speed control. Dr. Tignor is a 1961 graduate of the FHWA Highway Engineering Training Program.



ITDS: A Data Base Driven Interface to Traffic Models Using a Microcomputer

by
Alberto J. Santiago

Introduction

Developing and implementing traffic control strategies is complex and costly, involving significant investments in planning and in hardware acquisition, installation, and maintenance. In most cases, limitations of time, personnel, and cost, together with the obvious practical problems associated with disturbing existing traffic movements, preclude extensive field experimentation with alternative control strategies.

In response to this problem, the Federal Highway Administration (FHWA) and others have developed over the past 20 years a number of computer programs that can evaluate and/or optimize different traffic control strategies before committing the financial resources necessary to design the strategies and implement them in the field.

Extensive use of these computer programs has demonstrated their potential as effective tools in developing traffic control strategies that reduce motorist operating costs; vehicle fuel consumption and emissions; planning, design, and implementation costs of new control strategies; and costly and inconvenient retrofits when problems in a strategy are detected only after implementation.

However, differences in data requirements and input formats, the need to be comfortable working in a computer environment, and the perceived difficulty of using these computer programs—hereafter referred to as traffic models—have deterred some traffic engineers and analysts from using these powerful tools.

This article describes the Integrated Traffic Data System (ITDS), a set of microcomputer programs that solves many of these problems by providing an easy-to-use interface to a wide range of existing traffic models. ITDS allows the user to maintain a local traffic data base and easily generate input data sets for various traffic models in a user-friendly manner.

Common Problems With Traffic Models

Although traffic models are far more efficient and effective than other forms of complex analytical procedures, their use involves inherent problems in model selection, data requirements, and data coding.

Model selection

Traffic models were designed to run on mainframe computers and, in most cases, perform independent functions (simulation or optimization) for different applications (isolated intersections, arterials, grid networks, and/or freeways in urban, suburban, and/or rural scenarios) at different levels of detail (macroscopic or microscopic). These limitations in function, application, and detail imply that various traffic models must be used to develop networkwide, comprehensive control strategies.

Model selection also depends on available computers, model documentation (users manuals or software manuals), training (accessibility and willingness to attend training sessions), and support from the model developer.

Extensive documentation on model selection is available, however, to assist analysts in decisionmaking.

Data requirements

The availability of all of the data required by the models must be considered. Because traffic models were developed by different sources over time, their data requirements are similar but not identical. This implies that model selection dictates the data requirements which, depending on the data currently available, may impose the need for additional data collection efforts—an expensive proposition that affects the other equally important considerations, quality and compatibility. The output of any traffic model is only as good as the data that are used as input. If the data used as input reflect the "real-world" operation of the network, the model results will be accurate. Factors such as data collection procedures, separate data collections over long periods of time, and accuracy of equipment used directly affect the quality of the data and thus the representation of the traffic network by the models, no matter how sophisticated the models are. It is also important to note that problems associated with the quality and compatibility of the data are user-dependent and cannot be readily resolved.

Data coding

Coding, or manually processing, data is a tedious, time-consuming process requiring considerable personnel, expertise, and financial support and is the main reason traffic models are now used only to a limited degree.

Input formats and the results reported vary considerably from model to model. The user is required to reformat the original data to be compatible with the input format of the model to be used, run the program, get a copy of the results, manually reformat the portion of that output required by a second model, reformat any other data required by the second model that was not used or reported by the first model, run the second program, and continue in this manner until the process is completed for all models used and any possible or feasible alternatives. This repeated manual handling and processing of data introduces repeated chances for error, further jeopardizing the integrity of the data.

Advantages of Traffic Models

If such is the case, why bother to use traffic models? Very simply, it is less expensive than any other form of complex analytical procedure. The extra costs associated with the use of traffic models—training and computer use—are easily offset by the speed, flexibility, and accuracy of the results obtained. Additionally, training is a one-time cost per model used and usually pays for itself on the first application.

Common traffic control problems such as determining the impacts of implementing a pair of one-way streets in a downtown area, developing traffic control strategies to account for the closure of a section of roadway in an arterial, or updating the signal phasing and timing plans in an urban area to provide progression and reduce delay require considerable effort to resolve manually, and their solutions usually are inflexible in the sense that they are specific to the condition and cannot accommodate variances readily. (For example, "what if" two or three pairs of one-way streets, rather than one pair, were to be implemented?) Traffic models provide this flexibility with minimal additional effort and certainly at less cost than manual methods.

Any action taken to resolve, or at least minimize, problems associated with using traffic models will greatly promote their use, resulting in the development and implementation of better traffic control strategies.

ITDS—A New Concept

FHWA developed ITDS to resolve problems associated with data availability and coding. ITDS is a microcomputer-based system that quickly and easily generates input data sets extracted from a locally managed traffic data base for traffic simulation and signal timing optimization programs. The system is designed for traffic engineers and analysts who use, or intend to use, existing traffic models to develop and test traffic control strategies.

The main features of ITDS include the following:

- Menu-driven software with online assistance for easy, user-friendly access.

- Networkwide traffic data base storage on a hard disk that allows high-storage capacity and access speed.
- Data base maintenance using the state-of-the-art CODASYL (*Co*nference *On DA*ta *SY*stems *L*anguages) type data base management system.
- Input data sets for traffic models generated from either querying the data base or from user-supplied data.
- Job submission to and retrieval from a remote mainframe computer where the models could be executed by means of communication lines.
- Ability to use an optimization model's output as input to other traffic models.
- Data base management security.
- Data requirements listing, on a per model basis, for all interfaced models.
- Adaptability to meet future needs including interfacing to other traffic models and the use of color graphics, light pens, and "mouse."

With the exception of the job submission and retrieval features, all of the system's features relate directly or indirectly to the data base and its management. Therefore, the most important task in developing ITDS was to design a data base structure that could store any kind of traffic engineering data in a generic manner and still be readily accessible to any external application software (traffic models). This requirement led to the development of the data base approach.

The Data Base Approach

A data base is a centralized collection or storage of data for use in one or more particular applications. In traffic engineering, these data include the physical and operational characteristics of a traffic network. In most traffic modeling applications, specific means of handling data storage requirements have been developed. Typically, this data storage has been in the form of fixed-length sequential or "flat" files, which is appropriate for most standalone uses.

Because ITDS was designed to interface to a wide range of models, it has a more substantial data management and requirement problem than do most previous applications. For this reason, the heart of ITDS is a formal Data Base Management System (DBMS)—a collection of software that organizes, stores, and retrieves data items in a data base. ITDS represents the first known formal application of data base management theory to traffic engineering.

A DBMS in this application provides the following advantages:

- A means for sharing data among several different user applications. This first point is the most important. The DBMS provides a "universal" view of the traffic data base, which is independent of any particular application but from which each application can draw the subset of data it needs.
- A systematic and efficient means of storing and retrieving data from the data base.
- Flexibility for expanding the data base structure.
- Control over updates and changes, thus maintaining the integrity of the data base.

System Design and Implementation

In addition to developing a data base approach, other ITDS design goals can be summarized as follows:

- Portability—ITDS must be usable on a wide range of microcomputer systems. Also, the software must be designed so that any machine-specific code is localized in a single subroutine library.
- Low cost—ITDS should function with off-the-shelf hardware systems that are affordable to local traffic engineering organizations.
- Ease of use—ITDS should be easy to learn and use, and the advanced user should not be burdened with unnecessary tutorial information.
- Expandability—ITDS should be designed to grow and adapt to new environments. This includes interfacing to new traffic models as they are developed as well as interfacing to existing models as they are implemented in microcomputer versions.
- Versatility—ITDS should be able to store all kinds and amounts of traffic data. Preferably the quantity of data that can be stored should be limited only by the storage capacity of the computer.
- Economical—ITDS should take advantage of existing software components, where possible, to save developmental time and funds.

These design goals had a strong influence on the selection of software and hardware components and on the overall implementation approach.

Software components

ITDS has four categories of internal software components—the screen editor, the model interfaces, the DBMS, and the data base editor.

The screen editor, a general purpose interface between the ITDS software and the user's terminal screen, allows screen "forms" to be presented to the user. Each form typically consists of labeled fields for supplying various data values, along with explanatory text. Default or previously input values automatically are supplied for each field. The user can change or insert values in the various fields by moving a cursor to the field using the up, down, left, and right arrow keys at the console keyboard and then simply typing in the new value. Range checking and validation are performed automatically, and errors are reported at the bottom of the screen. Online help is available for any field at any time.

The screen editor is a much enhanced version of one developed originally for the U.S. Department of Transportation's Urban Mass Transportation Administration.

The second set of ITDS software components, the model interfaces, produces "card image" input files for the various traffic models. These fixed 80-column record length files contain all of the input data and commands to run their respective models. The model interfaces ensure that the correct data values are placed in the appropriate columns on each line (card) of the file.

The data placed in these files come from as many as four sources—the ITDS data base, the user's console, values from a previous input deck, and the models' built-in defaults. The user always has the final selection because values can be modified on the screen before being accepted.

The model interfaces also retrieve selected model output information for storage in the local data base. Current plans are to attempt to retrieve and store only the signal timing plans in this manner, allowing a user, for example, to retrieve optimal timing plans output by an optimization model such as TRANSYT-7F, store these data, and retrieve them for input to a detailed simulation model such as NETSIM.

As noted earlier, one of the most important components of ITDS is the DBMS. ITDS is built around the MDBS-III DBMS, an extended CODASYL network-type DBMS, which is designed as a library of software tools for interfacing to a user's application program. The MDBS-III DBMS was selected because it was the only microcomputer-based system available at the time that met design requirements for portability, security, data storage capacity, and, most importantly, ability to interface to a standardized programming language.

The final component of ITDS, the data base editor, is a menu-driven program that allows the user to create and update a data base of traffic engineering data. The menus are presented in a hierarchical sequence for easy access to the various data base components.

Several ITDS software components are external to the ITDS code itself, including the communications software, the design modification utility (DMU), and, of course, the traffic engineering models themselves.

The communications software downloads the card image input files to a remote mainframe or minicomputer where the modeling and analysis actually could be performed. As microcomputers become more powerful, all of the traffic models may be able to be run locally on the microcomputer itself, eliminating the need for communication with a remote site and simplifying the use of ITDS.

The DMU allows the user to perform certain modifications to the data base, including expanding the data base size and changing passwords and user names.

Software and hardware specifications

ITDS was developed using the Pascal MT+ language running under the CP/M-86 operating system. This language was chosen for the following reasons:

- Pascal MT+ was the only Pascal compiler at the time that conformed to the proposed ISO standard.
- Pascal MT+ is available for a variety of 8- and 16-bit computers, which assured the standardization and portability of the code.
- The nature of Pascal helps the programmer design efficient modular code that is maintained and updated easily.
- A first version of what was to be the screen editor portion of ITDS already was coded using Pascal.
- Pascal MT+ worked well with other ITDS components selected, such as the operating system and DBMS.

ITDS's initial development and testing were performed on an IBM-PC using the CP/M-86 operating system. This system can be implemented on 8-bit machines such as the Apple-II; however, 16-bit implementation allows greater speed and efficiency. Since the decision was made to use CP/M, the MS-DOS operating system has emerged as the dominant system for 16-bit environments. ITDS easily was converted from CP/M-86 to MS-DOS environment because machine and operating system specific code had been isolated in one subroutine library. The imminent release and support of ITDS will be only for the MS-DOS version.

ITDS does not include communication software. Files can be transmitted to and from a remote mainframe computer using a number of free "public domain" modem packages such as MODEM-7, PC-TALK, and KERMIT. Communication also can be accomplished by means of a local area network.

Expandability and modularity

ITDS has been designed with the future in mind. Because ITDS's data base structure is independent of any particular model's requirements, new and revised models generally can be interfaced to ITDS by adding only a new "deck" formatting module. Modifications to the data base structure, if required, should be minor and would not affect the operation of the system's other components.

As more and more mainframe traffic engineering models are implemented on microcomputer systems, ITDS can provide a standardized, easy-to-use interface. This eliminates a common problem of converting mainframe software to microcomputer use—providing an easy-to-use "front end" to the program.

ITDS's modular design makes it easy to add new components to the system. One enhancement that lends itself nicely to ITDS is the use of high-resolution color graphics, which can be extremely useful when entering complex network data such as geometrics or signal timing plans. Enhancements of this kind currently are underway.

Status

ITDS's software and documentation have been completed. The system will be released to the general public shortly, pending the signing of the distribution agreement for the DBMS. This agreement will enable FHWA to distribute ITDS, with the DBMS, for a small fee to cover the copying and handling expenses. The initial release of ITDS will include four major programs—DBedit, DBprint, NETSIM interface, and TRANSYT-7F interface.

The DBedit program allows the user to create and maintain the central data base and provides an option for segregating the data base for the entire network into user-definable subnetworks. The DBprint program creates hardcopies of the information stored in the data base and provides for a limited data base querying capability.

The NETSIM and TRANSYT-7F interfaces are the programs that create the input data sets (for the respective traffic models) by querying the data base. The TRANSYT-7F interface supports both the mainframe and microcomputer versions of the model. The NETSIM interface was designed for the "TRAF" NETSIM, which is expected to be released later this year.

Interfaces for additional traffic models, such as PASSER II, MAXBAND, SOAP, SIGOP III, and the computerized Highway Capacity Manual, are being developed as part of the ITDS support and maintenance activities. Graphics capabilities also are being developed, and the data base querying capabilities are being enhanced. These capabilities will be available on future ITDS releases during 1987.

Summary

ITDS efficiently allows for the storage of a generic traffic data base that interfaces with user-friendly, menu-driven programs for the creation of input data sets for various traffic models.

ITDS fills the gap between mainframe and microcomputer technology as related to traffic modeling. Traditionally, traffic models have been developed to run on mainframe computers. ITDS has taken full advantage of state-of-the-art microcomputer hardware and software, enabling the preprocessing of data to create input files offline, job submission and output retrieval, and the automatic use of optimization programs' output as input to other models. ITDS is thus the middle step between the traditional approach of creating input files manually and using a mainframe computer for processing and the innovative approach of creating input files and executing the programs locally and interactively at a microcomputer.

Additionally, ITDS reduces considerably the overhead costs associated with traffic models—training costs and costs associated with coding and submitting input files for processing. It provides information on the data requirements, therefore reducing to a minimum the data collection efforts. It provides an accessible, manageable, and centralized data base, and, last, but not least, ITDS provides for a simple, user-friendly work environment.

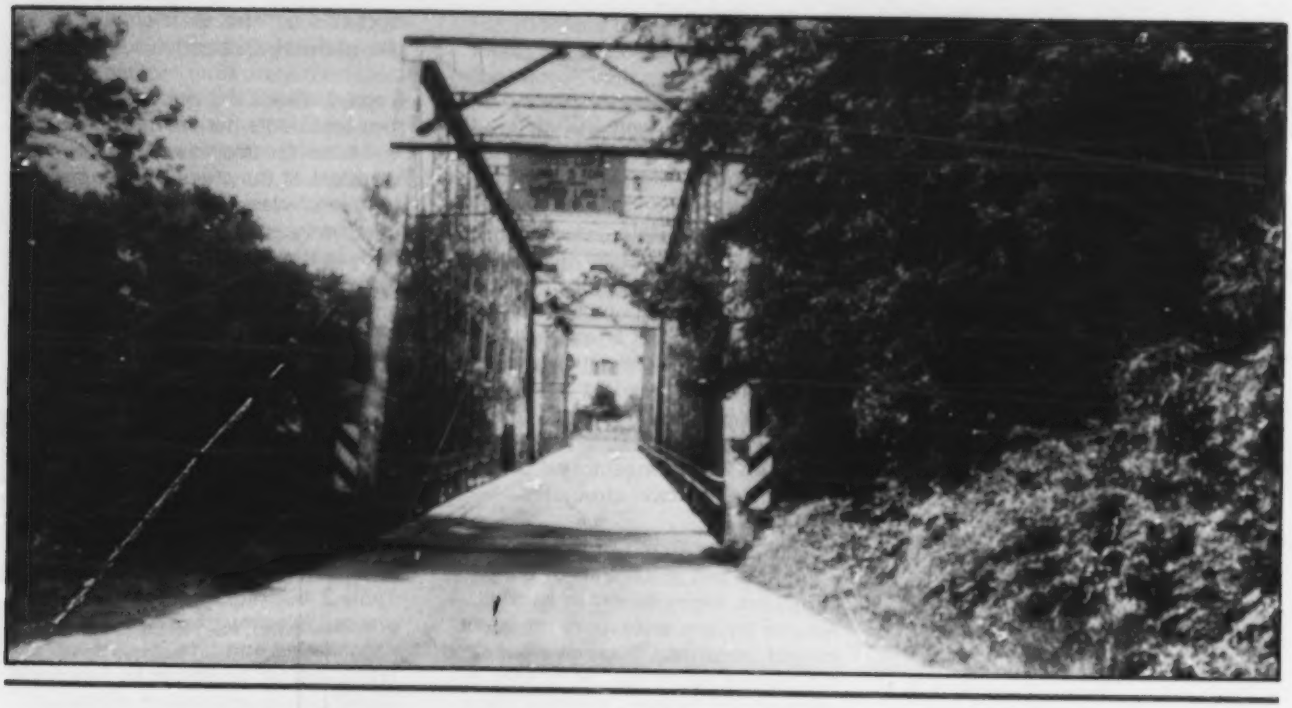
An important contribution of the ITDS project has been the development of a data base schema covering the data needs of a range of traffic engineering and network analysis models. The resulting data model has been designed to adapt to the changing needs of traffic engineering simulation and optimization tasks and also can be adapted to other transportation applications such as planning, mass transit, and safety, specifically in accident record management.

From a highway transportation perspective, the scenario for the 1980's is a very challenging one, calling upon the traffic engineering community to maximize the performance of our highway system. Our Nation's dependence on the movement of people and goods cannot tolerate any less. To cope with this challenge, major traffic engineering actions requiring accurate analysis tools must be planned and pursued aggressively. ITDS is the powerful tool that permits the use of traffic models in an efficient and effective manner, resulting in better traffic control strategies.

Readers interested in additional information on ITDS should contact the author at the following address:

Federal Highway Administration
Office of Safety and Traffic Operations R&D
Traffic Systems Division, HSR-10
6300 Georgetown Pike
McLean, Virginia 22101-2296
(703) 285-2027

Alberto J. Santiago is a highway research engineer in the Traffic Systems Division, Office of Safety and Traffic Operations Research and Development, FHWA. As project manager of FCP Project 2Q, "Urban Network Control," he coordinates, monitors, plans, and conducts research activities related to computerized signal systems, highway capacity, traffic simulation, and signal timing optimization programs. Mr. Santiago's principal areas of interest include traffic modeling, microcomputer applications to traffic engineering, and computer graphics.



Accident Analysis of Highway Narrow Bridge Sites

by
Charles P. Brinkman and King K. Mak

Introduction

Information on traffic accidents at bridge sites suggests a potential safety problem and the need for more detailed data on the problem. In the early 1970's, bridge-related accidents in the States of Virginia and Kentucky, for example, not only constituted a high percentage of all accidents, but also accounted for a disproportionate number of fatalities and injuries. (*1, 2*)[1] Bridge-related accidents were found to be approximately twice as likely to result in a fatality as a typical accident.

Of particular concern are "narrow" bridges whose diminished widths may increase the risk of single-vehicle collisions with roadside appurtenances such as bridge ends, railings, or approach guardrails as well as collisions with other vehicles. Also, many narrow bridges are structurally deficient because of their ages.

A research study sponsored by the Federal Highway Administration (FHWA) examined the extent and nature of the narrow bridge accident problem.[2] This article presents selected major findings and recommendations from this study.

Study Approach

Data on the physical and operational characteristics of bridges and their approach roadways were compiled from the computerized bridge and roadway inventory data files from the States of Arizona, Michigan, Montana, Texas, and Washington. Accident data were assembled from State accident files for all reported accidents occurring on or within 500 ft (152.4 m) of these bridges for a 3-year period using a milepoint matching process. The data base contained bridge, roadway, traffic, and accident data on 11,880 bridges and 24,809 accidents that occurred on these bridges or within their approach areas.

[1] Italic numbers in parentheses identify references on page 133.

[2] K.K. Mak and L.R. Calcote, "Accident Analysis of Highway Narrow Bridge Sites," Final Report, Federal Highway Administration and National Highway Traffic Safety Administration, Contract No. DOT-FH-11-9285, Washington, DC, February 1983.

Bridges included in the study data base had to meet the following criteria:

- The bridges had to be on State highway systems.
- The bridges had to be overpass structures (excluding culverts) carrying mainline vehicular traffic. For twin structures included in the bridge inventory file as two separate bridges, only the first of the two bridges was selected for analysis.
- No traffic control signals could be on the bridges or within the approach areas to the bridges.
- All key data elements on the bridges had to be known.

Another important consideration was the definition for what constitutes a narrow bridge. The "narrowness" definition used in this study was as follows:

- One lane, a total width of 18 ft (5.5 m) or less.
- Two lanes, a combined total width of 24 ft (7.3 m) or less.
- Total approach roadway width is greater than total bridge width and either the bridge shoulder width is less than 50 percent of the approach roadway shoulder width or the bridge shoulder width is at least 50 percent of the approach roadway shoulder width.

This definition generally was consistent with that used in NCHRP Report No. 203. (*3*) However, the further breakdown of up to 50 percent and greater than 50 percent shoulder reduction was arbitrary.

It should be emphasized that the study findings apply only to bridges meeting the study criteria and should not be extrapolated or extended to bridges not meeting these criteria.

General Bridge Characteristics

Because only bridges on State highway systems were included in the study, more than 90 percent of the bridges studied were in rural areas (table 1). Because there are few one-lane bridges on State highway systems, two-lane single structures accounted for 81.7 percent of the bridges studied, 95.6 percent of which were on rural arterials or collectors. Two-lane twin structures accounted for another 12.1 percent of the study bridges, two-thirds of which were on Interstate highways. The study thus concentrated on two-lane single and twin structures.

Overall, 71.9 percent of the single structures and 39 percent of the twin structures were defined as narrow. Narrow bridges were more prevalent in rural areas than in urban areas, and the percentage of narrow bridges decreased with higher functional class. Most bridges were straight and level, indicating the old practice of making alignment changes on the approach roadways.

The average two-lane single structure studied was 169 ft (51.5 m) long, 27.7 ft (8.4 m) wide with 11-ft (3.4-m) lanes, and had an approach roadway 29.8 ft (9.1 m) wide. The average daily traffic (ADT) volume usually was under 1,000 vehicles per day. For two-lane twin structures, the average bridge was 245 ft (74.7 m) long, 36.8 ft (11.2 m) wide with 12-ft (3.7-m) lanes, and had an approach roadway 40 ft (12.2 m) wide. Most of the twin structures had an ADT volume greater than 8,000 vehicles per day.

Extent of the Bridge Accident Problem

Table 2 shows the accident frequencies (accidents per year per bridge) and rates (accidents per million vehicles) of the study bridges by functional classification. Accident frequencies were higher on urban bridges than on rural bridges because of the higher traffic volumes in urban areas. However, when traffic exposure was taken into account, the accident rates were higher on rural bridges than on urban bridges. Also, accident frequencies generally declined with lower functional class while accident rates increased, probably reflecting the effect of differences in traffic exposure and design standards.

Table 3 illustrates the severities, expressed in terms of percent incapacitating and fatal injuries, of bridge-related accidents by functional classification and lane stratification. The severity of accidents on rural bridges was significantly higher than that on urban bridges (11.4 percent versus 5.8 percent incapacitating and fatal injuries), possibly because single-vehicle accidents were more frequent (51.9 percent) on rural bridges while multi-vehicle accidents were predominant (60.5 percent) on urban bridges. Single-vehicle accidents were much more severe than multi-vehicle accidents, with more than twice the percentage of fatal and incapacitating injuries (12.5 percent versus 6.2 percent). Other factors, such as higher speeds on rural highways, also may contribute to this difference in severity.

The study found that single-vehicle accidents were the predominant kind of accident for one-lane (73.5 percent) and two-lane (46.8 percent) single structures and for two-lane twin structures (53.8 percent), while multi-vehicle accidents were the overwhelming majority on the other kinds of structures. Two-lane single structures had significantly higher accident severities (11.4 percent incapacitating and fatal injuries) than did the other kinds of structures.

The study also found that for single-vehicle accidents, impacts involving bridge parapet ends were the most severe, resulting in incapacitating and fatal injuries in almost 30 percent of the reported accidents. By comparison, the severity of guardrail collisions was only 9.5 percent incapacitating and fatal injuries, and the severity of bridge rail collisions was 12 percent incapacitating and fatal injuries—the average for all fixed-object or run-off-the-road accidents. By using proper approach guardrails and transition treatments, the severity of bridge end accidents could be reduced significantly. For multi-vehicle accidents, head-on collisions were the most severe (23.6 percent incapacitating and fatal injuries), while the overall severity was 6.2 percent incapacitating and fatal injuries.

The Effect of Bridge Narrowness

The effect of bridge narrowness on safety was examined, and accident frequencies and rates for the various bridge types and narrowness categories are summarized in table 4. For one-lane bridges, the mean accident rate was higher for bridges wider than 18 ft (5.5 m) than for bridges narrower than 18 ft (5.5 m); however, the difference was not statistically significant and the sample size was too small for reliable results.

For two-lane undivided single structures, in general mean accident rates decreased with increasing bridge width for bridges narrower than the approach roadways. However, for bridges wider than the approach roadways, the highest mean accident rate was at bridge widths between 20 and 22 ft (6.1 and 6.7 m). Also, differences in mean accident rates between bridges narrower than the approach roadways and bridges wider than the approach roadways are significant for bridge widths up to 20 ft (6.1 m) but not significant for widths greater than 20 ft (6.1 m) (fig. 1).

For four-lane undivided single structures, the accident rate was highest for bridges with more than a 50-percent shoulder reduction. The accident rate decreased significantly for bridges with a shoulder reduction less than or equal to 50 percent and increased for bridges with no shoulder reduction, although these differences were not significant.

Shoulder reduction appeared to have some effect on accident rates for multi-lane single structures. However, the differences are not statistically significant, probably because of the small sample sizes.

For two-lane twin structures, bridges with widths of 24 ft (7.3 m) or less and bridges with a shoulder reduction greater than 50 percent had similar accident rates (fig. 2). The accident rates decreased significantly for bridges with a shoulder reduction less than or equal to 50 percent and remained little changed for bridges with no shoulder reduction. This suggests that there may be little difference in safety benefit between two-lane twin structures with no shoulder reduction or a reduction less than or equal to 50 percent. However, the 50-percent shoulder reduction breakpoint is arbitrary, and the results could change with different breakpoints.

Table 1.—Distribution of bridges

Functional classification	Number	Percent
Urban:		
Interstate	323	2.7
Major arterial	622	5.2
Minor arterial	206	1.7
Collector	26	0.2
Subtotal	1,177	9.8
Rural:		
Interstate	839	7.1
Major arterial	2,109	17.8
Minor arterial	2,246	18.9
Collector	5,509	46.4
Subtotal	10,703	90.2
Total	11,880	100.0

Lane stratification	Number	Percent
One-lane	88	0.7
Single structure, undivided		
Two-lane	9,701	81.7
Four-lane	274	2.3
Single structure, divided		
Four-lane	174	1.5
Other	95	0.8
Twin structure		
Two-lane	1,440	12.1
Other	108	0.9
Total	11,880	100.0

Table 2.—Accident frequencies and rates by functional classification

Functional classification	Accidents per year per bridge[1]	Accidents per million vehicles
Urban:		
Interstate	5.04	0.517
Major arterial	2.66	0.656
Minor arterial	1.58	0.852
Collector	0.78	0.479
Average (weighted)	3.08	0.649
Rural:		
Interstate	1.09	0.456
Major arterial	0.71	0.634
Minor arterial	0.51	0.762
Collector	0.20	0.812
Average (weighted)	0.44	0.738

[1] Accident rates were computed on the basis of the bridge length plus 500 ft (152.4 m) in each direction.

Table 3.—Distribution of accident severity

Functional classification	Percent incapacitating and fatal injury
Urban:	
Interstate	5.6
Major arterial	5.9
Minor arterial	6.5
Collector	1.7
Average (weighted)	5.8
Rural:	
Interstate	10.7
Major arterial	12.2
Minor arterial	9.5
Collector	12.9
Average (weighted)	11.4

Lane stratification	Percent incapacitating and fatal injury
One-lane	5.9
Single structure, undivided	
Two-lane	11.4
Four-lane	5.6
Single structure, divided	
Four-lane	6.1
Other	3.5
Twin structure	
Two-lane	8.7
Other	5.7
Overall average (weighted)	8.9

Table 4.—Accident frequencies and rates by bridge narrowness

		Bridge narrowness				
		Number of lanes	Bridge width (ft)	Shoulder reduction	Accidents per year per bridge[1]	Accidents per million vehicles
Single structures	Undivided	1	≤18	–[2]	0.12	1.177
			> 18	–	0.15	2.025
		2	≤18, <Approach	–	0.38	1.884
			≤18, ≥Approach	–	0.09	0.751
			18-20, <Approach	–	0.25	1.036
			18-20, ≥Approach	–	0.11	0.765
			20-22, <Approach	–	0.48	1.194
			20-22, ≥Approach	–	0.28	1.213
			22-24, <Approach	–	0.35	0.816
			22-24, ≥Approach	–	0.21	0.874
			>24	>50%	0.70	0.746
			>24	≤50%	0.45	0.661
			>24	None	0.37	0.586
		4	N/A	>50%	2.95	0.876
				≤50%	1.47	0.597
				None	2.11	0.791
	Divided	4	N/A	>50%	2.99	0.681
				≤50%	2.15	0.565
				None	2.57	0.498
		Other	N/A	>50%	14.24	0.790
				≤50%	3.48	0.407
				None	4.28	0.398
Twin structures	Divided	2	≤24	–	1.66	0.577
			>24	>50%	2.35	0.562
			>24	≤50%	1.72	0.452
			>24	None	1.16	0.437
		Other	N/A	>50%	6.17	0.753
				≤50%	8.35	0.834
				None	4.75	0.562
		Total			0.70	0.729

[1]Accident rates were computed on the basis of the bridge length plus 500 ft (152.4 m) in each direction.

[2]Little or no shoulder width.

1 ft = 0.305 m

For multi-lane twin structures, bridges with no shoulder reduction had lower accident rates than did bridges with a shoulder reduction. However, the differences are not statistically significant, probably because of the small sample sizes.

Shoulder reduction seemed to have a marginally significant effect on accident severity on twin structures, with higher accident severities for bridges with a shoulder reduction greater than 50 percent and lower severities for bridges with a shoulder reduction less than or equal to 50 percent. Bridge narrowness did not appear to have any effect on accident severity for single structures.

Statistical Analysis

Extensive statistical analyses were conducted to determine the relationships of accident frequency, rate, and severity at bridge sites to bridge and approach characteristics. Various statistical techniques were used, including analysis of variance, correlation analysis, factor analysis, simple and multiple linear regression, and discriminant analysis. The results are highlighted below.

Results from the discriminant analysis indicate that bridges with accidents could reasonably be distinguished from bridges with no accidents based on certain physical and operational characteristics at bridge sites. For undivided bridges, the discriminant variables, in order of importance, are ADT, roadside distraction, percent shoulder reduction, degree of bridge curvature, curb presence, bridge length, degree of approach curvature, and delineation. For divided bridges, the discriminant variables are ADT, roadside distraction, percent shoulder reduction, barrier rating[3], Bridge Safety Index (BSI)[4], percent bridge grade, speed limit, and bridge length. It should be noted, however, that these discriminant variables are not necessarily causal factors.

[3]A composite index of ratings on the presence/absence and conditions of bridge rail, approach guardrail, transition rail, and end treatment.

[4]A composite index of ratings on 10 factors relating to bridge and traffic characteristics.

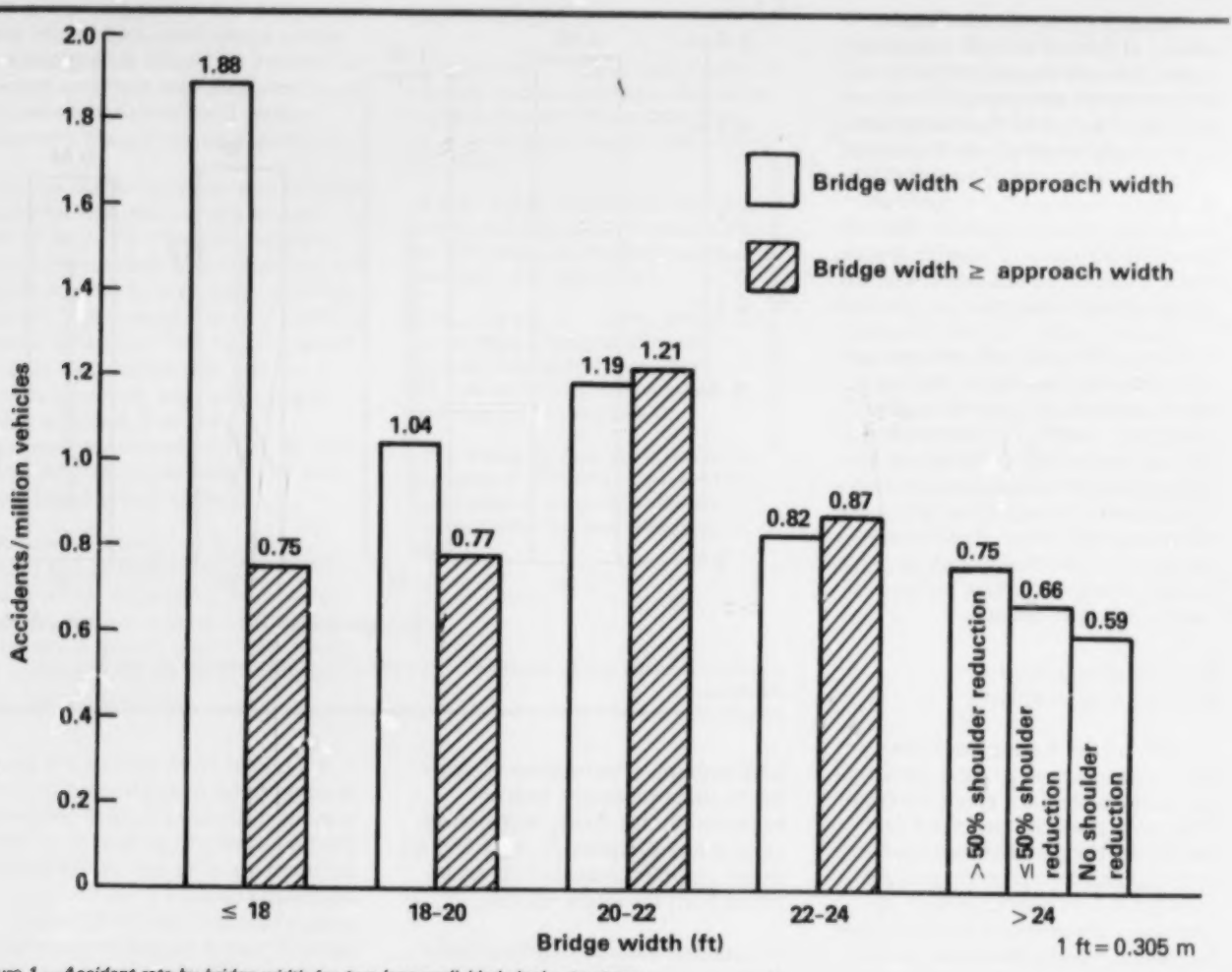


Figure 1.—Accident rate by bridge width for two-lane undivided single structures.

Results of discriminant analyses on accident severity (bridges with no incapacitating and fatal accidents versus bridges with incapacitating and fatal accidents) indicated that accident severity on bridges is little affected by the physical and operational characteristics at the bridge sites.

Stepwise multiple linear regression analyses were conducted to relate the physical and operational characteristics at bridge sites to accident frequency, rate, and severity for bridges with accidents. The regression results for accident frequency and rate are generally fair, with about 25 percent of the sample variations explained ($R^2 = 0.25$). However, the regression results for accident severity are poor, with R^2 values of under 10 percent in most cases, again indicating that accident severity is little affected by the physical and operational characteristics at bridge sites.

Although accident studies quantify the extent of a particular problem and provide valuable insight, they can only provide general guidance to specific safety design questions such as acceptable bridge width and shoulder reduction. Accident studies are limited by inaccurate accident location; unreported accidents; the lack of readily available data on important highway characteristics; the rare and random nature of traffic accidents, making large sample sizes necessary; and the interrelationships of accident causal factors, confounding the establishment of strong statistical relationships. Thus, safety design decisions also must be based on the pure physics of the problem, traffic operational measures of effectiveness, and human factors research.

Indepth Study of Bridge Accident Characteristics

Indepth data were gathered on 124 single-vehicle bridge accidents in which the first impact was with a bridge rail, bridge parapet end, or approach guardrail to provide insights into accident details not available from police accident data, such as impact speed and angle, vehicle kinematics, and damages to bridge hardware. Over three-quarters of the accidents involved more than one impact; one-half of these accidents involved three or more impacts. The injury severity of an accident increased with the total number of impacts, clearly indicating the role of subsequent impacts in the severity of these kinds of accidents.

One-quarter of the vehicles were yawing at greater than 30 degrees at impact. Vehicle yawing probably would have no adverse effect for impacts with typical bridge rail or guardrail sections; however, yawing could increase the severity of impacts with bridge rail or parapet and guardrail ends. Also, it could increase the possibility of rollovers. Vehicle yawing possibly should be a parameter in the design of barrier systems.

Also, a surprisingly high percentage of the impacts resulted in improper barrier performance (for example, overriding, vaulting, or penetration), and this potential problem should be examined closely. Also, subsequent impacts were prevalent for barrier collisions at bridge sites. Post-impact trajectory of vehicles should be studied closely for bridge rail and approach guardrail designs.

Conclusions and Recommendations

Bridges are more dangerous than the highway system as a whole, and narrow bridges can be a safety problem. This study provided directions for identifying bridges that may have a potential accident problem and are candidates for countermeasure applications. Discriminant functions and regression models developed in this study may be used to identify bridges with potential safety problems. However, it is essential to maintain design consistency in applying bridge accident countermeasures so that driver expectancy will not be violated; the application of countermeasures should be considered both on an individual bridge basis and on a systemwide basis.

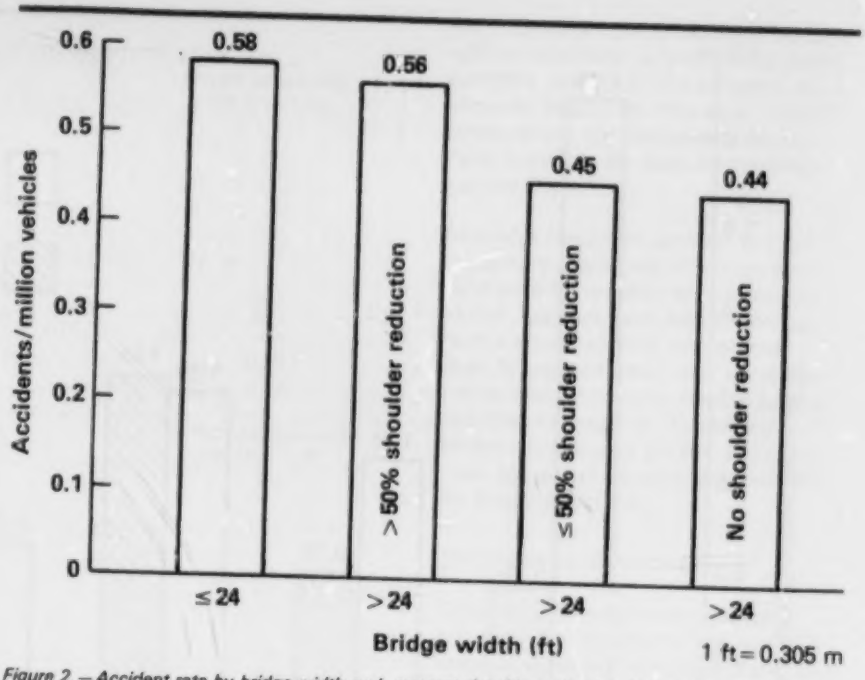


Figure 2.—Accident rate by bridge width and percent shoulder reduction for two-lane twin structures.

Although the effectiveness of accident countermeasures was not evaluated in this study, some observations and suggestions regarding accident countermeasures may be inferred from the study results.

- Countermeasures requiring major reconstruction (for example, widening bridges more than the minimum widths required for bridges to remain in place given in the AASHTO "Green Book" (*4*) and realigning approach roadways) may not be cost-effective on the sole basis of safety benefits, given the lack of strong relationships found in this study between accidents and any of the physical features at bridge sites.

- If a bridge or its approach roadway is going to be reconstructed for other reasons such as structural deficiency, the bridge should be built to a design standard equal to that of the existing approach roadway or to the new design standard for the functional class of road if further improvements are planned for the approach roadway and/or the route involved. The study did not provide definitive guidance concerning acceptable bridge width and shoulder reduction. Certainly, as a minimum, where the full approach roadway width is greater than the width of the bridge, the width of new or reconstructed bridges should not be less than the minimum required roadway widths for new and reconstructed bridges. (*4*) However, this minimum requirement should not be construed as the optimal safety standard.

• It is also suggested that bridges not have curbs. Extremely sharp curves or steep grades should be avoided on bridges and their approach roadways, but gentle horizontal and vertical alignment should not be a problem.

• Bridge rail and parapet end impacts are by far the most severe bridge-related accident. Properly installed approach guardrail and transitions will significantly reduce accident severity and are highly recommended accident countermeasures. The frequencies of impacts with bridge rails and approach guardrails are nearly equal, which suggests that barrier countermeasures should include combined retrofits of the bridge rail and approach guardrail systems.

• Roadside distraction is strongly related to accident frequency, rate, and severity, suggesting that better land use control around bridge sites to minimize access points and potential conflicts may be an effective accident countermeasure.

REFERENCES

(1) M.H. Hilton, "Some Case Studies of Highway Bridges Involved in Accidents," Highway Research Record No. 432, *Highway Research Board,* Washington, DC, 1973.

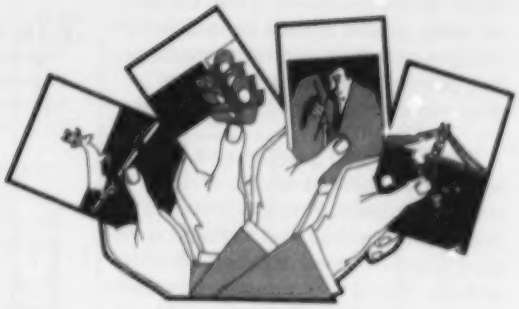
(2) K.R. Agent, "Accidents Associated with Highway Bridges," Research Report No. 427, *Kentucky Bureau of Highways,* Lexington, KY, May 1975.

(3) D.L. Ivey et al., "Safety at Narrow Bridge Sites," National Cooperative Highway Research Program Report No. 203, *Transportation Research Board,* Washington, DC, June 1979.

(4) "A Policy on Geometric Design of Highways and Streets," *American Association of State Highway and Transportation Officials,* Washington, DC, 1984.

Charles P. Brinkman is a project manager in the Traffic Safety Research Division, Office of Safety and Traffic Operations Research and Development, FHWA. He is involved in research to improve highway safety evaluation.

King K. Mak is a research engineer with the Texas Transportation Institute, Texas A&M University System. He was with Southwest Research Institute when the study discussed in this article was conducted. Mr. Mak has been active in the highway safety area since 1970, with emphasis in accident data analysis, and has worked on various studies sponsored by FHWA, the National Highway Traffic Safety Administration, and other Federal and State agencies.



Recent Research Reports You Should Know About

The following are brief descriptions of selected reports recently published by the Federal Highway Administration, Offices of Research, Development, and Technology (RD&T). The Office of Engineering and Highway Operations Research and Development (R&D) includes the Structures Division, Pavements Division, and Materials Division. The Office of Safety and Traffic Operations R&D includes the Traffic Systems Division, Safety Design Division, and Traffic Safety Research Division. The reports are available from the source noted at the end of each description.

Requests for items available from the RD&T Report Center should be addressed to:

Federal Highway Administration
RD&T Report Center, HRD-11
6300 Georgetown Pike
McLean, VA 22101-2296
Telephone: 703-285-2144

When ordering from the National Technical Information Service (NTIS), use PB number and/or the report number with the report title and address requests to:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

Implementation of Polymer Impregnation as a Bridge Deck Sealant, Report No. FHWA/RD-85/094

by Structures Division

The surface treatment procedure for partially polymer impregnating concrete bridge decks was refined and evaluated on eight full-sized highway bridges in various geographical locations over a period of 8 years. This report discusses the field evaluation phase of this effort. Cost data of bridge deck impregnation are included in the report. Results are reported on an extensive series of chloride ion intrusion tests performed. An appendix containing the most recent surface impregnation construction specifications also is included.

The report may be purchased from NTIS (PB No. 85 248698).

Polymer Concrete Used in Redecking a Major Bridge, Report No. FHWA/RD-85/079

by Structures Division

This report describes the successful use of polymer concrete for supporting the precast deck elements to the existing girders and stringers on the Woodrow Wilson Bridge, which crosses the Potomac River between Virginia and Maryland. Over 30 mixture designs were tested to formulate a suitable mixture based on the casting of mockup specimens and physical strength tests. An unusual gap problem was observed between the concrete slab and the underneath cast polymer pedestals in the sawcut mockup specimens. A solution was found by creating an inverted cone of polymer concrete, which increased a fill hole from a 2½-in (63.5-mm) diameter to a 6-in (152.4-mm) diameter base at the bottom of the precast slab interface with the pedestal.

The report may be purchased from NTIS (PB No. 85 249290).

Evaluation of the Howard Frankland Bridge Surveillance and Control System in Tampa, Florida, Report No. FHWA/RD-85/061

by Traffic Systems Division

The Federal Highway Administration and the Florida Department of Transportation jointly funded the design and construction of a computerized surveillance and control system (SCS) for the Howard

Frankland Bridge in Tampa, Florida. Three functions of the SCS are to detect incidents, manage traffic on the bridge, and divert bridgebound traffic during incidents causing serious delays. The SCS began full operations in June 1983. This report discusses the evaluation of the SCS.

The SCS identified 45 percent of all traffic incidents; however, it significantly improved response time for only one-third to one-half of all incidents. Considering all incidents, 89.6 percent were managed with lane closure; however, compliance with lane closure was low. For a significant portion of their duration, incidents were not protected by signing because of delays in detection, confirmation, and implementation. Nine percent of all incidents were managed with diversion. Compliance with diversion was low despite the finding that diversion offered substantial travel time savings. SCS component failures were a problem, and the SCS had a cost-effectiveness ratio of 1.2 to 1.0.

It was concluded that non-automated sources of incident detection, particularly motorist-aid phones, can be as reliable or more reliable than automated sources. Closed-circuit television can be useful in monitoring critical facilities such as bridges and tunnels. Diversion systems are feasible but applicable to a narrow range of problems, and SCS's require considerable maintenance and should be designed for reliability and easy servicing.

The report may be purchased from NTIS (PB No. 85 230274).

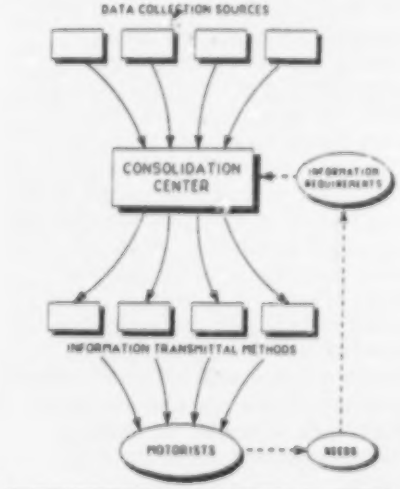
Concepts for a Low-Cost Motorist Information System, Final Report and Appendix A, Report No. FHWA/RD-85/038, and Appendix B—Case Study, Report No. FHWA/RD-85/039

by Traffic Systems Division

These reports discuss a study that developed and evaluated concepts for a low-cost, practical motorist information system that would decrease travel time and improve safety, comfort, and convenience. A list of motorist needs was developed and divided into dynamic information, which changes frequently and primarily includes information on traffic congestion and incidents; semidynamic information, which changes occasionally and primarily relates to motorist services, such as gas, food, lodging, and attractions information; and static information, which changes infrequently and includes information such as highway geometry and emergency services.

Existing systems for addressing motorist needs were identified and evaluated. These systems are described by three basic functions: Data collection, data consolidation, and information transmittal to motorists. These three functions form the basis of the concepts for improved motorist information systems.

The reports may be purchased from NTIS (PB Nos. 85 243657 and 85 243665).



Functional Diagram of a Motorist Information System

Symbolic Sign for Oversized-Truck Route Signs, Report No. FHWA/RD-85/064

by Traffic Systems Division

The Surface Transportation Assistance Act of 1982 mandates greater national uniformity in truck size and weight, requiring some States to raise their limits, at least for trucks traveling on the Interstate System and portions of the Federal-Aid Primary System. The law provides for the States to mark these routes with appropriate signs. The study described in this report evaluated six candidate symbolic signs that could be used for these nationally designated truck routes.

Truck drivers participated in tests of recognition time, meaning, and preference, and other drivers participated in tests of visibility, meaning, and preference.

The findings indicate that a side-view, double-trailer symbol sign had the best recognition time and the best meaning scores. Even though in the visibility study this symbol sign did not have the longest recognition distances, no other symbol was labeled as an oversized truck as often as the double-trailer symbol, possibly because the other candidate signs were confused with the presently used NO TRUCKS sign. Finally, the double-trailer symbol sign was overwhelmingly preferred by all test subjects over the other candidate signs.

The report may be purchased from NTIS (PB No. 85 241883).

DISCOUNT RATES AND UNREPORTED ACCIDENTS

Sensitivity of Resource Allocation Models to Discount Rate and Unreported Accidents, Report No. FHWA/RD-85/092

by Traffic Safety Research Division

Resource allocation models aid highway safety planning decisions by prioritizing projects based on their costs and benefits. A sensitivity analysis was conducted to see how project selection is affected by failure to adjust the accident data base for underreporting and, separately, by the choice of discount rate and accident-cost methodology used in computing accident costs and the present value of future benefits. The analysis used an optimization model developed by the Texas Transportation Institute for the Federal Highway Administration and a data base from Alabama that contained accident data from 216 high-accident locations as well as data on proposed countermeasures.

The choice of discount rate and accident cost methodology can have a significant impact on the highway safety projects selected and the benefits realized. This effect will be particularly noticeable if the choice of discount rate is an extreme one. The project selection is likely to be relatively stable in the discount rate range of 3 to 7 percent that was recommended for sensitivity analysis. Any project selected within this range will have little effect on total benefits and costs.

Unreported accidents also can play a decisive role in highway safety project selection. For the particular data set used in this analysis, projects selected changed little at budget levels of $300,000 to $900,000 when the percent of reported accidents was reduced. However, at budget levels of $1.2 million to $1.5 million, project selection changed considerably with a loss in total benefits. This suggests it is very important to account for the underreporting of accidents when a reporting threshold of towaway, injury, and fatal accidents is used.

The report may be purchased from NTIS (PB No. 85 243806).

Benefits and Safety Impact of Night Work Zone Activities, Report No. FHWA/RD-85/067

by Safety Design Division

Through a literature review and discussions with highway and transportation officials in several States, information was obtained on questions and concerns relating to the planning, safety, and traffic control aspects of night maintenance and construction activities and their advantages and disadvantages. The information obtained was used to develop the general guidelines presented in this report on when and how maintenance and construction work should be performed at night. The report presents case studies illustrating the activities required in different kinds of night maintenance and construction activities. Although there are many potential disadvantages of working at night, it is believed that through the experience that has been gained and proper planning and special concern for construction worker and motorist safety, night work is feasible for selected maintenance and construction activities.

The report may be purchased from NTIS (PB No. 85 213320).

Improvements and New Concepts for Traffic Control in Work Zones, Volumes 1-4, Report Nos. FHWA/RD-85/034-037

by Safety Design Division

Volume 4, **Speed Control in Work Zones**, of this report series presents the results of a study to develop effective methods of slowing traffic to an acceptable speed in work zones. Factors considered in the study included cost, motorist and worker safety, institutional constraints, and probability of success in obtaining the desired speed.

Field tests were conducted to evaluate the short-term effectiveness of flagging, law enforcement, changeable message signs, and lane-width reduction in work zones on an undivided multilane urban arterial, an urban freeway, and two rural highways. Several different configurations of the four speed control methods were evaluated.

The results indicated that flagging and law enforcement were the most effective methods evaluated. These results are based on data collected over 2 to 3 hours. Additional evaluations are planned to determine if flagging and law enforcement are effective over a longer period of time.

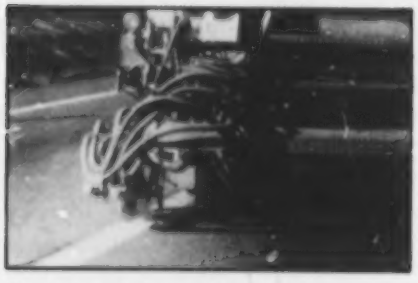
This report also contains a summary of the three other volumes in this series. Volume 1, **Effects of Traffic Control on Four-Lane Divided Highways**, Volume 2, **Implementation of Work Zone Traffic Control**, and Volume 3, **Abbreviated Marking Patterns in Work Zones**, may be purchased from NTIS (PB Nos. 85 207561, 85 207579, and 85 207587). Limited copies of Volume 4 are available from the RD&T Report Center.

Implementation/User Items "how-to-do-it"

The following are brief descriptions of selected items that have been completed recently by State and Federal highway units in cooperation with the Office of Implementation, Offices of Research, Development, and Technology (RD&T), Federal Highway Administration. Some items by others are included when the items are of special interest to highway agencies.

When ordering from the National Technical Information Service (NTIS), use PB number and/or the report number with the report title and address requests to:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161



Organic Yellow Traffic Paint, Report No. FHWA-TS-84-227

by Office of Implementation

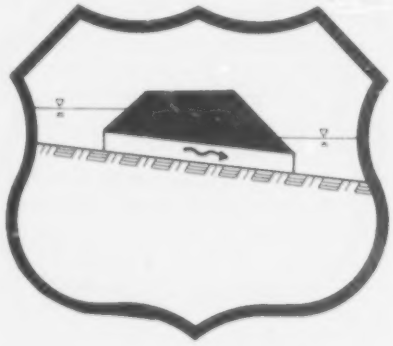
This report summarizes the results of a field evaluation of two organic yellow paints—a 50/50 mixture of white and yellow and a control section consisting of each participating State's standard yellow traffic paint. Also discussed are the paint formulations, laboratory and field tests, and the results of the States' evaluations. The study recommends that the color standard for yellow traffic paint be revised to allow a broader range, specifically the lighter yellow shades.

The report may be purchased from NTIS.

Hydraulic Design of Highway Culverts, Report No. FHWA-IP-85-15

by Office of Implementation

This comprehensive culvert design publication combines culvert design information contained in Hydraulic Engineering Circulars No. 5, No. 10, and No. 13 with hydrologic, storage routing, and special culvert design considerations. Culvert design methods are presented for both conventional culverts and culverts with inlet improvements. Also included are storage routing techniques that permit the designer to account for upstream ponding effects. Special design considerations for unique culvert applications, erosion and sediment control, debris control, and structural appurtenances are briefly discussed and referenced. The appendixes of the publication contain the equations and methodology used to construct the design charts, information on hydraulic resistance for corrugated metal culverts, and methods of optimizing culvert design using performance curves.



The report may be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402 (Stock No. 050-001-00298-1).

1983 National Value Engineering Conference—Proceedings Synopsis, Report No. FHWA-TS-85-208

by Office of Implementation

This report documents the proceedings of the 1983 National Value Engineering Conference held in Kissimmee, Florida, on November 16-18, 1983. The conference was sponsored by the Florida Department of Transportation in cooperation with the Federal Highway Administration's Office of Engineering and the Office of Implementation in the Offices of Research, Development, and Technology.

Included in the report are edited transcripts of the presentations, technical papers, and question-and-answer panel review sessions that were completed during the 3-day conference. Of particular interest were the presentations and panel sessions that covered new and unique applications of value engineering techniques to functionally analyze a State department of transportation's organizational structure and obtain balanced technical and cost-saving solutions to highway design and construction problems.

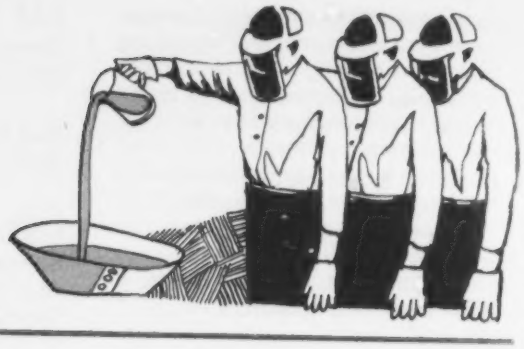
The report may be purchased from NTIS.

Dynamic Compaction of a Sanitary Landfill, Report No. FHWA-TS-85-227

by Office of Implementation

This report provides background information and describes construction operations involved in the dynamic compaction of a newly completed sanitary landfill that was crossed during the relocation and construction of U.S. Rte. 71 near Springdale, Arkansas. The report includes a history of the project, location and plans for the highway, geological survey data of the area, information concerning the landfill itself, and analyses of alternative solutions. Also included are details outlining the method used in determining the specialty contractor required for such a project. Load test results and implementation of a long-term monitoring plan to determine the extent and rate of settlement also are outlined.

The report may be purchased from NTIS.



New Research in Progress

The following new research studies reported by FHWA's Offices of Research, Development, and Technology are sponsored in whole or in part with Federal highway funds. For further details on a particular study, please note the kind of study at the end of each description and contact the following: Staff and administrative contract research—*Public Roads* magazine; Highway Planning and Research (HP&R)—performing State highway or transportation department; National Cooperative Highway Research Program (NCHRP)—Program Director, National Cooperative Highway Research Program, Transportation Research Board, 2101 Constitution Avenue, NW., Washington, DC 20418.

FCP Category 1—Highway Design and Operation for Safety

FCP Project 1A: Traffic and Safety Control Devices

Title: Driver Risk Perception and Performance. (FCP No. 31A3134)
Objective: Develop a measure of driver risk perception. Determine the relationship between risk perception and other driver characteristics such as age, experience, and degree of impairment. Examine the effects of traffic control devices, geometrics, and visual guidance factors (lighting and delineation) on driver risk perception. Ascertain how the driver's perception of risk translates into actual risk-taking and other behavior in the highway environment.
Performing Organization: Comsis Corporation, Wheaton, MD 20902
Expected Completion Date: March 1988
Estimated Cost: $198,000 (FHWA Administrative Contract)

FCP Project 1P: Night Visibility

Title: Enhancement to the DOT/FHWA Highway Simulator (HYSIM). (FCP No. 31P1033)
Objective: Provide an engineering design for the first planned enhancement in visual display capability for the FHWA HYSIM. Increase resolution, add scene complexity and higher brightness levels, and include interacting vehicles in the scene.
Performing Organization: Systems Technology, Inc., Hawthorne, CA 90250
Expected Completion Date: December 1986
Estimated Cost: $212,130 (FHWA Administrative Contract)

FCP Project 1T: Roadside Safety Hardware

Title: Rollover Caused by Concrete Safety Shape Barriers. (FCP No. 31T2452)
Objective: Determine causes of vehicle rollover and seek solutions. Review accident data. Use computer simulation with measured vehicle inertial and suspension properties to study the effects of front-wheel drive, wheel inertia, barrier coefficient of friction, nonlevel terrain, and asphalt overlays. Conduct full-scale tests to validate the analytical results, if required.
Performing Organization: Texas A&M Research Foundation, College Station, TX 77843
Expected Completion Date: March 1988
Estimated Cost: $150,000 (FHWA Administrative Contract)

FCP Category 2—Traffic Control and Management

FCP Project 2L: Electronic Devices for Traffic Control

Title: Malfunction Management of Traffic Signals. (FCP No. 32L1242)
Objective: Develop conceptual design and preliminary specifications for automatic malfunction detection of traffic signal control hardware. Determine which traffic control intersection hardware is most prone to failure. Analyze frequency of failure, cost of providing the hardware to detect failure, and alternative communication links and modes for the most cost-effective ways of communicating with isolated noninterconnected intersections to assess equipment status.
Performing Organization: Magnavox, Inc., Falls Church, VA 22042
Expected Completion Date: March 1987
Estimated Cost: $235,400 (FHWA Administrative Contract)

FCP Project 2P: Urban Freeway Management

Title: Corridor Traffic Management for Temporary Flow Disruptions. (FCP No. 32P2172)
Objective: Develop and document guidelines and case study examples for the application of corridor traffic management techniques to improve critical link flow disruptions. Include flow reductions as well as complete restrictions from either planned or unplanned incidents such as bridge

repair, major freeway reconstruction, large-truck accidents, and bridge collapse. Use existing traffic simulation models and traffic assignment techniques to demonstrate alternative management techniques.
Performing Organization: GAI Consultants, Inc., Monroeville, PA 15146
Expected Completion Date: September 1987
Estimated Cost: $158,000 (FHWA Administrative Contract)

FCP Category 3—Highway Operations

FCP Project 3B: Environmental Management

Title: Design Guidelines for Protective Systems for Spills of Hazardous Materials on the Highway System. (FCP No. 33B1062)
Objective: Develop design guidelines for protective systems for incorporation in the highway system. Evaluate alternative designs and determine effectiveness. Emphasize the feasibility of incorporation of protective measures in existing highways as well as into new designs.
Performing Organization: Kansas State University, Manhattan, KS 66506
Expected Completion Date: October 1987
Estimated Cost: $149,520 (FHWA Administrative Contract)

FCP Category 4—Pavement Design, Construction, and Management

FCP Project 4A: Pavement Management Strategies

Title: Cost Comparison of Maintenance Activities and a Selected Cost/Benefit Application. (FCP No. 44A2072)
Objective: Develop cost data model of routine maintenance activities for in-house and contractor forces. Develop a cost comparison analytical model for contract versus in-house accomplishment of routine maintenance activities. Prepare a case study cost/benefit analysis of roadside vegetation management alternatives. Conduct an analysis of the potential cost/benefits of a Bermuda grass release program for roadside vegetation.
Performing Organization: Texas Transportation Institute, College Station, TX 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1986
Estimated Cost: $145,000 (HP&R)

Title: Pavement Management Application of New Data Base. (FCP No. 44A3402)
Objective: Enhance ongoing software developments associated with the Utah Department of Transportation common data base composed of key parameters from planning, safety, and pavement condition. Concentrate on providing information for pavement management applications.
Performing Organization: Utah Department of Transportation, Salt Lake City, UT 84114
Expected Completion Date: September 1987
Estimated Cost: $23,600 (HP&R)

FCP Project 4B: Design and Rehabilitation of Rigid Pavements

Title: Design of Rest Area Comfort Stations. (FCP No. 44B1111)
Objective: Develop design criteria for safety rest area to result in safe, clean, efficient, easy to maintain, and cost-effective rest area comfort stations and facilities. Determine usage, vehicles using the facility, and operation and maintenance costs. Evaluate alternative energy sources and applications. Investigate innovative building materials and methods and security and legal liability. Develop, implement, and evaluate prototype designs and develop a design manual for rest area comfort stations.
Performing Organization: University of Texas at Austin, Austin, TX 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: September 1988
Estimated Cost: $310,000 (HP&R)

Title: Thin Bonded Overlay Implementation. (FCP No. 44B1338)
Objective: Determine under what conditions (distress manifestations and remaining service life) thin bonded overlays are the most appropriate rehabilitation technique. Develop an outline of construction specifications to ensure good quality thin bonded concrete overlays. Evaluate various materials and their relative advantages and disadvantages and the strength, durability, and economics of different overlay thicknesses. Develop a users design and construction manual for thin bonded overlays.
Performing Organization: University of Texas at Austin, Austin, TX 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1988
Estimated Cost: $230,000 (HP&R)

Title: Materials and Methods for Undersealing Concrete Pavements. (FCP No. 34B2192)
Objective: Document current undersealing materials, problems, and advantages of their application and performance in inservice pavements. Identify other materials that may have improved ease of application and improved performance. Select the most promising materials based on costs and laboratory testing. Evaluate these promising materials in experimental pavement rehabilitation projects.
Performing Organization: Austin Research Engineers, Inc., Austin, TX 78745
Expected Completion Date: March 1988
Estimated Cost: $150,000 (FHWA Administrative Contract)

Title: Rigid Pavement Data Base. (FCP No. 44B2314)
Objective: Evaluate the needs for pavement condition survey data. Select appropriate sections and obtain pavement condition data and update condition data procedures. Investigate incorporating the pavement condition data into a data base management system, and make appropriate recommendations. Develop an integrated overlay design manual for rigid pavements using the existing data base and existing overlay design procedures for each kind of rigid pavement.
Performing Organization: University of Texas at Austin, Austin, TX 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1988
Estimated Cost: $190,000 (HP&R)

FCP Project 4C: Design and Rehabilitation of Flexible Pavements

Title: Design and Performance of Asphalt Concrete Pavement (ACP) Overlays on Concrete Pavements. (FCP No. 44C4254)
Objective: Develop guidelines and procedures to be used in the thickness and mix design of ACP overlays on concrete pavements.
Performing Organization: Texas Transportation Institute, College Station, TX 77843
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1988
Estimated Cost: $190,000 (HP&R)

Title: Treatment of Asphalt Mixtures With Lime and Antistripping Agents. (FCP No. 44C4374)
Objective: Determine the effectiveness of hydrated lime and selected liquid antistripping agents. Evaluate the relationships between test values for different mixtures and antistripping agents using indirect tensile test (wet-dry), Texas freeze-thaw pedestal test, Texas boiling test, and other tests. Evaluate field performance for different mixtures using different antistripping agents and relate test values to performance.
Performing Organization: University of Texas at Austin, Austin, TX 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1990
Estimated Cost: $300,000 (HP&R)

FCP Project 4D: Improved Flexible Binders

Title: Asphalt Behavior at Low Service Temperature. (FCP No. 34D1103)
Objective: Investigate the response of asphalts to varying cooling rates and repeated strains in the low temperature service range using newly developed methodology based on fracture mechanics. Determine how thermal cracking is initiated in asphalt pavements and how the initiation and propagation of cracks is affected by asphalt properties. Suggest methods to control this problem.
Performing Organization: Pennsylvania State University, University Park, PA 16802
Expected Completion Date: April 1988
Estimated Cost: $172,860 (FHWA Administrative Contract)

FCP Category 5—Structural Design and Hydraulics

FCP Project 5A: Bridge Loading and Design Criteria

Title: Design of Simple-Span Precast Prestressed Girders Made Continuous. (FCP No. 55A4012)
Objective: Investigate the behavior of precast, prestressed bridge girders made continuous by connections using cast-in-place slabs and diaphragms at the piers. Develop design procedures and guide specifications that can be used to compute elastic, inelastic, time-dependent, and ultimate moments commensurate with the degree of continuity developed by the connections at the piers.
Performing Organization: Contraction Technology Laboratory, Skokie, IL 60077
Expected Completion Date: December 1987
Estimated Cost: $242,000 (NCHRP)

Title: Anchorage Zone Reinforcement for Post-Tensioned Girders. (FCP No. 55A4022)
Objective: Develop design procedures for end and intermediate anchorage zones for post-tensioned concrete girders and slabs.
Performing Organization: University of Texas at Austin, Austin, TX 78712
Expected Completion Date: September 1988
Estimated Cost: $240,000 (NCHRP)

FCP Project 5K: Bridge Rehabilitation Technology

Title: Fatigue Evaluation Procedures for Steel Bridges. (FCP No. 55K2092)
Objective: Develop practical procedures that more accurately reflect the actual fatigue conditions in steel bridges and that can be applied for fatigue evaluation of existing or new bridges (specifically, determining fatigue-load ratings and estimating remaining life for existing bridges). Incorporate the procedures into AASHTO's manual for maintenance inspection of bridges and possibly future bridge design specifications.
Performing Organization: Case Western Reserve University, Cleveland, OH 44106
Expected Completion Date: September 1987
Estimated Cost: $200,000 (NCHRP)

Title: Distortion-Induced Fatigue Cracking in Steel Bridges. (FCP No. 55K2102)
Objective: Quantify the fatigue resistance of bridge details that are susceptible to distortion-induced fatigue cracking and evaluate the retrofit procedures used to repair such damage.
Performing Organization: Lehigh University, Bethlehem, PA 18015
Expected Completion Date: September 1988
Estimated Cost: $250,000 (NCHRP)

Title: Calibration of Bridge Capacity Estimates With Existing Test Data. (FCP No. 55K2112)
Objective: Assemble domestic and foreign test data to identify, quantify, and report significant aspects of observed behavior that are not now considered in load capacity estimates.
Performing Organization: University of Tennessee, Knoxville, TN 37996
Expected Completion Date: September 1987
Estimated Cost: $200,000 (NCHRP)

Title: Methods of Strengthening Existing Highway Bridges. (FCP No. 55K3052)
Objective: Evaluate the feasibility and cost-effectiveness of present strengthening methods as applied to various bridge types and identify cost-effective, innovative methods.
Performing Organization: Iowa State University, Ames, IA 50011
Expected Completion Date: December 1986
Estimated Cost: $150,000 (NCHRP)

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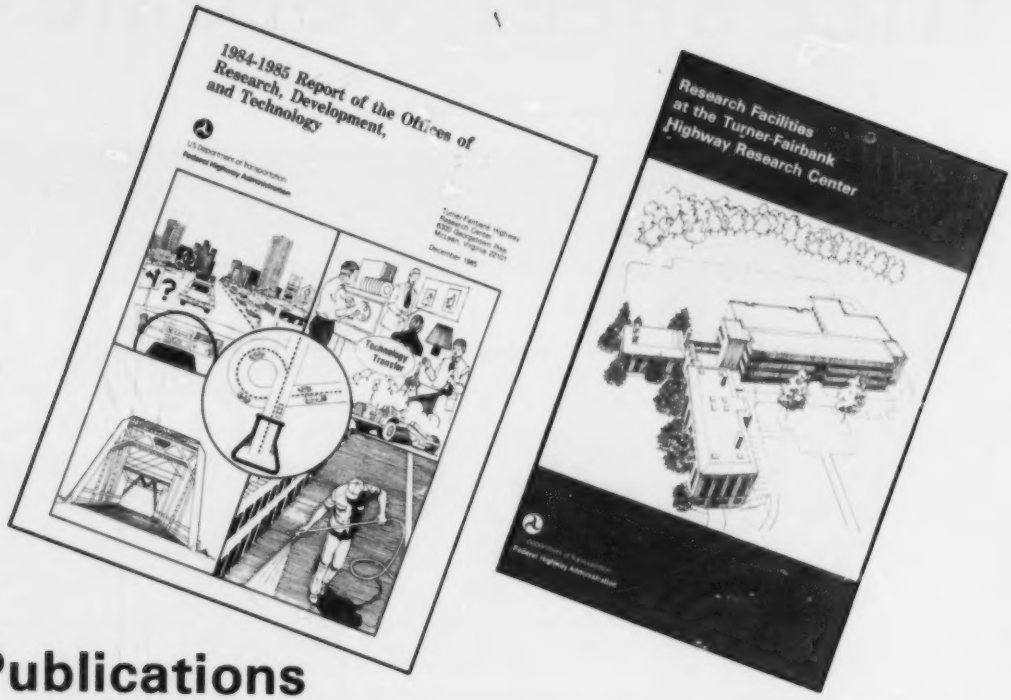

1984-1985 Report of the Offices of Research, Development, and Technology
Technology Transfer
Research Facilities at the Turner-Fairbank Highway Research Center

New Publications

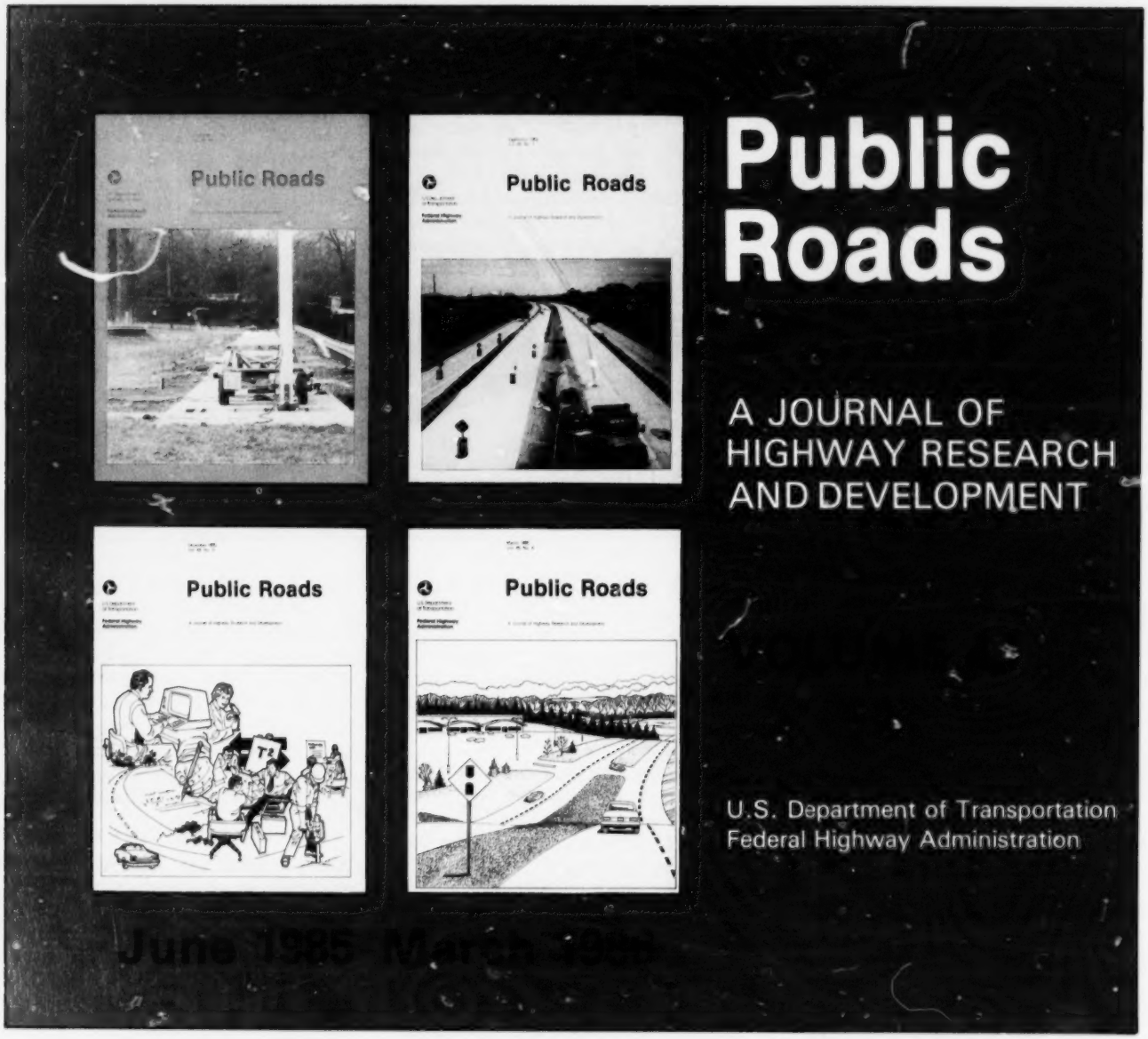
The Offices of Research, Development, and Technology (RD&T) have released their **1984-1985 Report of the Offices of Research, Development, and Technology.** This report is a continuation of the series of annual reports previously entitled "Federally Coordinated Program of Highway Research, Development, and Technology" and published for fiscal years 1974 through 1983. The latest report briefly discusses the goals and problems of the Federally Coordinated Program (FCP) of Highway Research, Development, and Technology and describes accomplishments in highway RD&T during fiscal years 1984 and 1985 in the areas of highway design and operation for safety; traffic control and management; highway operations; pavement design, construction, and management; and structural design and hydraulics. Also highlighted are other activities of the Offices of RD&T and the innovative research laboratories for FHWA in-house research at the Turner-Fairbank Highway Research Center in McLean, Virginia. The proposed Strategic Highway Research Program (SHRP), expected to be implemented in fiscal year 1987, also is outlined.

Also released by the Offices of RD&T is the brochure **Research Facilities at the Turner-Fairbank Highway Research Center** that describes the laboratory facilities at the Center. These laboratories greatly enhance the potential scope and quality of the Federal Highway Administration research program by allowing in-house studies of the fundamental aspects of chronic highway problems, special investigations and quick solutions for specific emergency problems, and the development of staff capabilities.

The brochure provides a brief description of the new laboratories in the Turner Building, the renovated laboratories in the Fairbank Building, and the outdoor testing facilities at the Center. The kind of research performed in the laboratories is described as well as the purpose of the research and innovative equipment used in gathering and processing data.

While supplies last, individual copies of the report and brochure are available without charge from the Federal Highway Administration, RD&T Report Center, HRD-11, 6300 Georgetown Pike, McLean, Virginia 22101-2296. (Telephone: 703-285-2144.)

TITLE SHEET, VOLUME 49



This issue of *Public Roads* includes the title sheet for volume 49 (June 1985–March 1986). Including the title sheet in the March issue (and in future March issues for subsequent volumes) is a change from previous volumes when the title sheets were published as separate flyers and mailed at the same time as the June issue.

As with previous volumes, the title sheet chronologically lists article titles and alphabetically lists authors' names.

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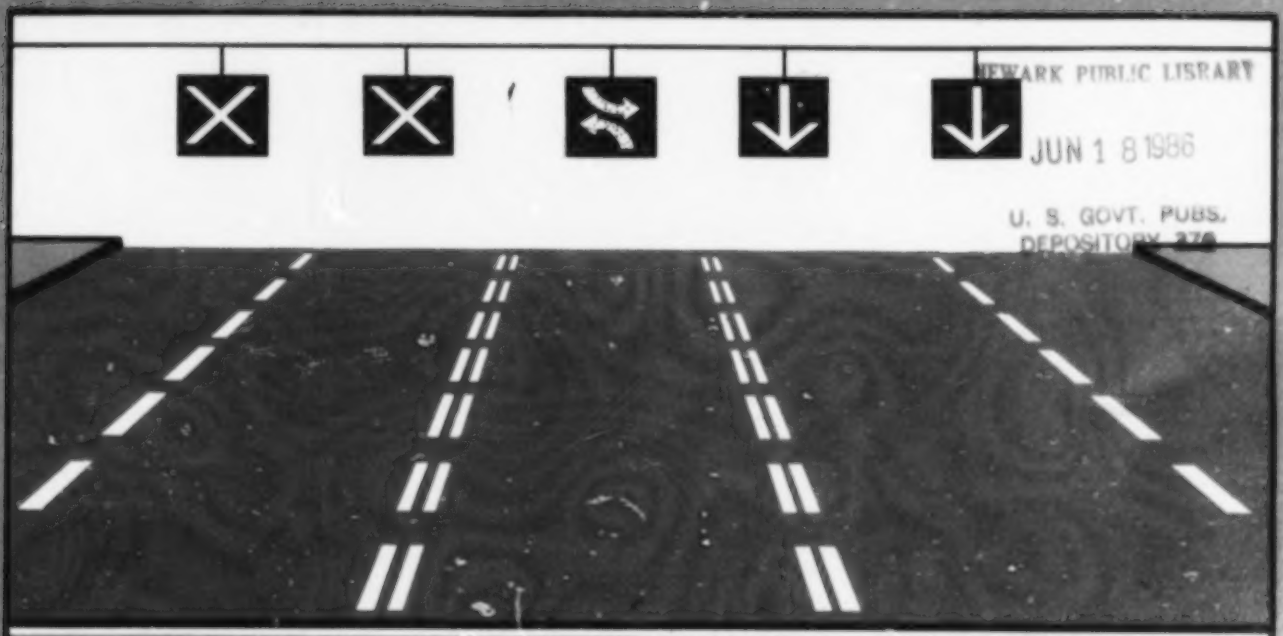

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SIGNALS AND SIGNS FOR REVERSIBLE FLOW TWO-WAY LEFT-TURN LANES

Public Roads

A Journal of Highway Research and Development

June 1986
Vol. 50, No. 1

U.S. Department of Transportation
Elizabeth Hanford Dole, *Secretary*

Federal Highway Administration
R.A. Barnhart, *Administrator*

U.S. Department of Transportation
Federal Highway Administration
Washington, DC 20590

COVER: In the FHWA study discussed in the lead article, reversible flow two-way left-turn lane traffic controls were developed and tested in the laboratory. Shown are the recommended signals to indicate this control treatment, and, as an alternate, the recommended static sign.

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The Secretary of Transportation has determined that the publication of this periodical is necessary in the transaction of the public business required by law of this Department.

Contents of this publication may be reprinted. Mention of source is requested.

Traffic Control for Reversible Flow Two-Way Left-Turn Lanes

by
Merton Rosenbaum

Introduction

Traffic carrying capacity on existing roadways can be increased with reversible flow lanes and two-way left-turn lanes. Although these control treatments most frequently are used individually, some jurisdictions successfully alternate both treatments on the same arterial because of a combination of peak-period congestion and increased roadside development.

Traffic control devices for signing and marking a reversible lane and standards for signing and marking a two-way left-turn lane are included in the "Manual on Uniform Traffic Control Devices" (MUTCD) (fig. 1). (*1*)[1] No standards have been established for alternating the application of these two treatments on the same lane at different times of the day. MUTCD signals, signs, and markings have been adapted and augmented to meet specific site requirements and economic considerations. On a five-lane arterial, for example, the center lane may be reversed for inbound morning and outbound evening peak periods and used as a two-way left-turn lane during offpeak periods. However, the lack of standards has resulted in nonuniform treatments that can confuse drivers unfamiliar with the roadway.

In response to requests to develop traffic controls for the combination use of reversible flow and two-way left-turn lanes, the Federal Highway Administration (FHWA) sponsored a study in which past and present reversible flow two-way left-turn lane (RF2WLTL) sites were reviewed, driver information requirements were determined, and candidate RF2WLTL traffic controls were developed and tested in the laboratory. (*2*) This article discusses this study and the research results, which have been used by FHWA to propose changes to the MUTCD. (*3*)

[1]Italic numbers in parentheses identify references on page 10.

Review of Existing RF2WLTL Sites

A literature review and discussions with highway officials identified 19 undivided arterial roadways in the United States that have used RF2WLTL's during the past 25 years. Site characteristics, including kind of control, operational features, roadway characteristics. and descriptions of traffic control systems, are given in table 1.

The researchers visited each of the 15 sites that remain in operation, observing and photographing portions of each operational time period—outbound peak, offpeak, and inbound peak periods. Motion pictures were taken while driving through the sites in each direction during each time period. Still photographs were taken of the signs, signals, and pavement markings being used.

For example, in figure 2, overhead lane-use signs used in Phoenix, Arizona, include word messages giving the times of day for alternating the use of the center lane. The center lane is marked for two-way left turns. Figure 3 shows supplemental signs used in Phoenix to indicate left-turn restrictions and center lane use.

The Speedway Boulevard and Grant Road sites in Tucson, Arizona, use red and green flashing beacons to call attention to entrance and exit signs and to combination symbol and word message signs mounted over the center lane (figs. 4–6). Extensive roadside development and commercial signs competing for the driver's attention are typical of many arterials where reversible flow lanes and/or two-way left-turn lanes are used.

On Georgia Avenue in Montgomery County, Maryland, red X and green arrow signals indicate directional lane use (fig. 7). The outbound end of this site is an Interstate highway interchange. The typical clutter of commercial signs is present as well as frontage roads serving commercial establishments. Initially a raised median was removed to provide a two-way left-turn lane to serve roadside development. However, as peak-hour volumes increased, the roadway evolved into the present RF2WLTL site.

Although most RF2WLTL sites alternate use of the center lane between peak-hour through movements and offpeak two-way left turns, two roadways—Peachtree Street in Atlanta, Georgia (fig. 8) and Nicholasville Road in Lexington, Kentucky (fig. 9)—have unique traffic patterns. On Peachtree Street, left turns are permitted from the two center lanes

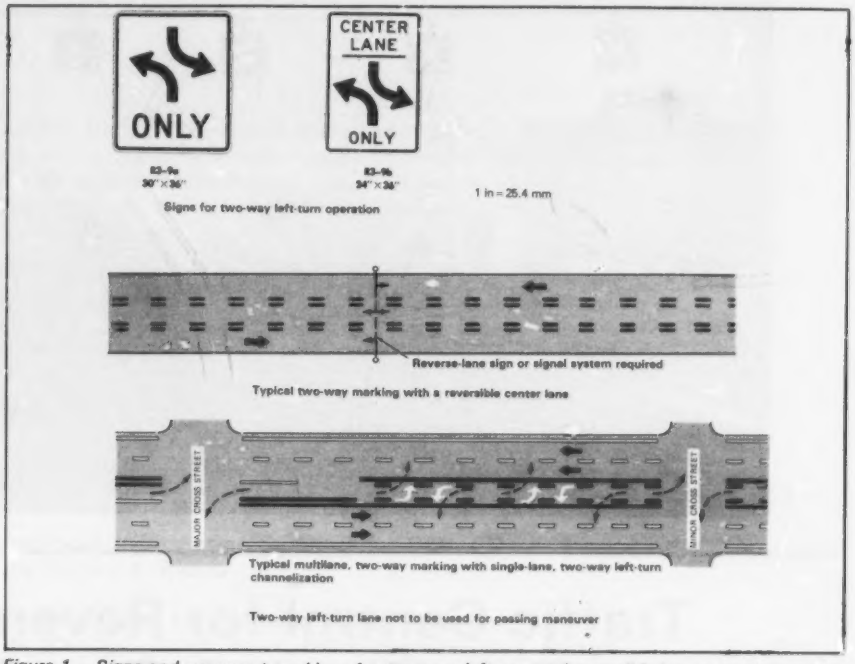

ONLY
CENTER LANE
ONLY
1 in = 25.4 mm
Signs for two-way left-turn operation
Reverse-lane sign or signal system required
Typical two-way marking with a reversible center lane
MAJOR CROSS STREET
MINOR CROSS STREET
Typical multilane, two-way marking with single-lane, two-way left-turn channelization
Two-way left-turn lane not to be used for passing maneuver

Figure 1.—Signs and pavement markings for two-way left-turn and reversible-lane operation used separately. (1)

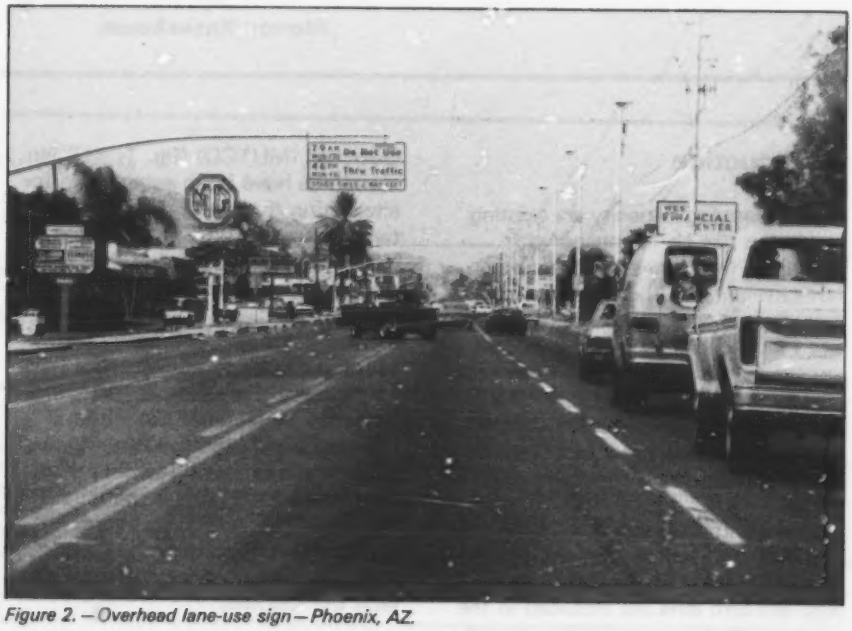


Figure 2.—Overhead lane-use sign—Phoenix, AZ.

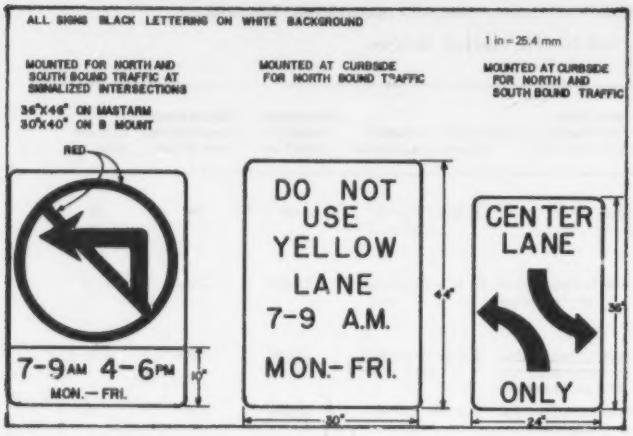

ALL SIGNS BLACK LETTERING ON WHITE BACKGROUND
1 in = 25.4 mm
MOUNTED FOR NORTH AND SOUTH BOUND TRAFFIC AT SIGNALIZED INTERSECTIONS
36"X48" ON MASTARM
30"X40" ON B MOUNT
MOUNTED AT CURBSIDE FOR NORTH BOUND TRAFFIC
MOUNTED AT CURBSIDE FOR NORTH AND SOUTH BOUND TRAFFIC
RED
7-9AM 4-6PM
MON.—FRI.
DO NOT USE YELLOW LANE 7-9 A.M. MON.-FRI.
CENTER LANE
ONLY

Figure 3.—Supplemental signs—Phoenix, AZ.

Figure 4.—Entrance signs—Tucson, AZ.

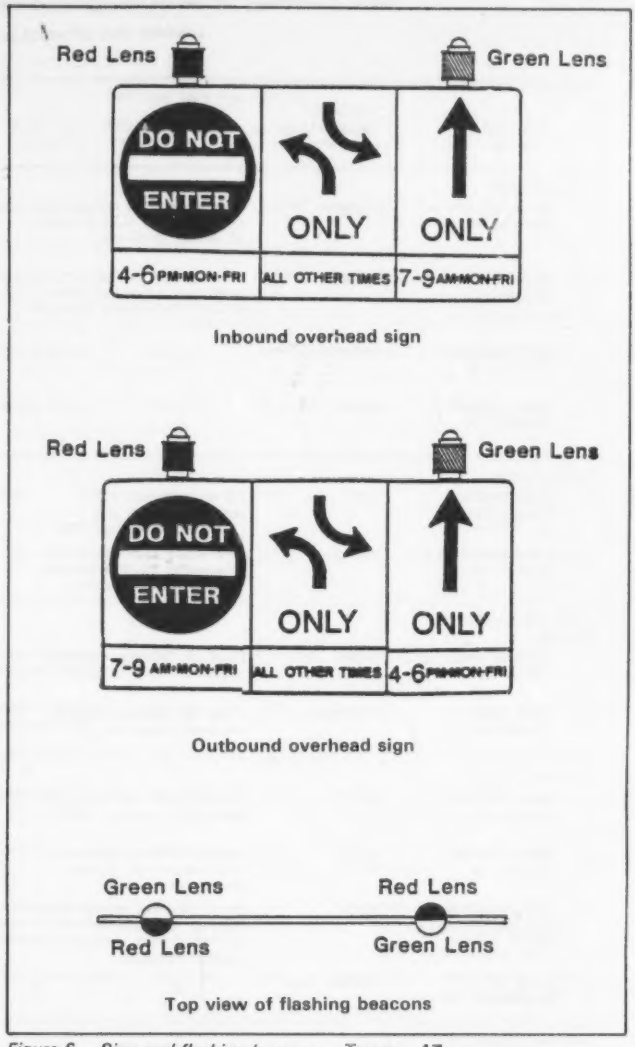


Figure 6.—Sign and flashing beacons—Tucson, AZ.

Figure 5.—Exit signs—Tucson, AZ.

Figure 7.—Lane-use signals—Montgomery County, MD.

Table 1.—Summary of reversible flow two-way left-turn sites—control, operational features, roadway characteristics, and traffic control devices

Site and control system	RF2WLTL installation date	Modifications and remarks	Peak-hour left-turn restrictions	Length (miles)	Number of lanes	Average daily traffic	Signalized intersections per mile
Sign controls							
1. Fifteenth Avenue, Phoenix, AZ	December 1959	Reversible flow operations eliminated in 1974 because of safety problems.	None	1.4	3	NA	NA
2. Grand River Avenue, Detriot, MI	December 1959	Reversible flow operations permitted since May 1947. NO LEFT TURN signs installed in 1977.	Prohibited	12.4	7	25,930	5.2
3. Seventh Avenue, Phoenix, AZ	January 1979		Prohibited only at signalized intersections	6.0	6	30,000	2.2
4. Seventh Street, Phoenix, AZ	August 1982		Prohibited only at signalized intersections	8.0	6	35,000	2.5
Traffic cones							
5. Sixth Street, Tucson, AZ	1975	1.8-mi reversible flow section on east end installed in August 1968.	Prohibited	1.6	5	14,660	3.8
6. Washington Street, Phoenix, AZ	May 1978	Reversible flow operations eliminated in 1979 because of high manpower costs.	Prohibited at some minor intersections	2.3	6	NA	NA
Signs and flashing beacons							
7. Speedway Boulevard, Tucson, AZ	August 1980	Flashing beacons added on overhead signs in 1982.	Prohibited	3.7	5	36,320	3.2
8. Grant Road, Tucson, AZ	June 1981	Flashing beacons added on overhead signs in 1982.	Prohibited	4.6	5	39,520	2.6
Lane-use signals							
9. Memorial Drive, Atlanta, GA	1957	Incandescent matrix signals upgraded in January 1983.	None	1.2	3	13,000	5.0
10. DeKalb Avenue, Atlanta, GA	1959	Roadway reconstructed in 1981 because of transit system construction.	None	3.4	3	NA	NA
11. Georgia Avenue, Montgomery County, MD	1980	Three lane-use signal spans removed to reduce driver confusion with intersection traffic signals.	Prohibited	0.4	7	79,450	5.0
12. Route 202, Manchester, ME	October 1982		None	0.5	3	13,670	2.0
Lane-use signals and overhead signs							
13. Norman Bridge Road/ Decatur Street, Montgomery, AL	1962		Prohibited for minor intersections only	0.6	3	12,850	3.3
14. Michigan Avenue, Dearborn, MI	September 1963	Fiber optic signals used in 1977 and upgraded in 1979.	Prohibited	1.0	5	46,270	6.0
15. Broadway, Tucson, AZ	1973	Removed lane-use signals from outer lanes.	Prohibited	2.0	5	33,680	2.5
16. Red River Street Austin, TX	October 1973	Reversible flow operations eliminated in 1982 because of street reconstruction.	Prohibited for minor intersections only	1.3	3	12,240	2.5
Special applications							
17. Peachtree Street, Atlanta, GA	October 1975	Reversible flow operations permitted since 1966. Two-way left-turn lane maintained during peak periods only.	None	1.1	6	47,000	NA
18. Nicholasville Road, Lexington, KY	March 1979	Signs added to explain two-way left-turn lane and yellow X. Two-way left-turn lane maintained at all times.	None	2.6	5	35,130	3.8
19. N.W. Seventh Avenue, Miami, FL	January 1975	U.S. DOT demonstration project—reversible lane for buses only. Reversible bus lane removed in 1976.	Prohibited	2.5 4.8	7 5	19,420 18,210	NA

1 mi=1.6 km; 1 ft=0.305 m; 1 in=25.4 mm

Table 1.—Continued

Streets per mile	Commercial driveways per mile	Residential driveways per mile	Pavement markings	Post-mounted signs	Overhead lane-use controls: Kind of control	Size	Number per mile	Kind of support	Entrance/ exit signing
NA	NA	NA	Two-way left-turn lane	NA	Static signs	3x9 ft	NA	Span wire	NA
25.2	35.0	0.2	Reversible lane	Left-turn restrictions	Series of three static signs	3x3 ft	6.0	Span wire	Overhead sign on western end of section only
20.3	45.2	15.5	Two-way left-turn lane	Left-turn and lane-use restrictions	Static signs	5x10 ft	4.0	Mastarm	Overhead sign
19.5	70.0	5.5	Two-way left-turn lane	Left-turn and lane-use restrictions	Static signs	5x10 ft	4.0	Mastarm	Overhead sign
28.1	32.5	10.0	Two-way left-turn lane	Left-turn and lane-use restrictions	None	—	—	—	Overhead sign on western end of section only
NA	NA	NA	NA	Barricades used to control traffic	None	—	—	—	Post-mounted sign
23.5	59.7	10.3	Two-way left-turn lane	Left-turn and lane-use restrictions	Static signs and beacons	4x9 ft	4.0	Mastarm	Overhead sign with beacons
19.1	86.7	17.2	Two-way left-turn lane	Left-turn and lane-use restrictions	Static signs and beacons	4x9 ft	4.0	Mastarm	Overhead sign with beacons
19.2	73.3	11.7	Reversible lane	None	Lane-use signals	24x30 in and 18x18 in	10.0	Span wire	Overhead signs
NA	NA	NA	Reversible lane	None	Lane-use signals	12x12 in	6.5	Span wire and mastarm	Overhead signs
22.5	60.0	0.0	Reversible lane	Left-turn restrictions	Lane-use signals over three center lanes	18x18 in	12.5	Span wire	Overhead lane control and post-mounted signs at entrance only
10.0	40.0	8.0	Two-way left-turn lane	Lane-use control	Lane-use signals	12x12 in	14.0	Span wire	Post-mounted sign at entrance only
28.3	36.7	45.0	Reversible lane	Left-turn restrictions	Lane-use signs; lane-use signals over center lane	12x12 in (signals)	11.7	Span wire	None
18.0	41.0	0.0	Reversible lane	Left-turn restrictions	Lane-use signals and variable message sign over center lane	18x24 in	7.0	Span wire	Post-mounted sign at entrance only
19.5	89.5	6.5	Two-way left-turn lane	Left-turn and lane-use restrictions	Lane use signals over three center lanes; variable message sign over center lane	12x12 in (signals)	8.0	Truss support	Overhead sign with beacons at entrance; without beacons at exit
NA	NA	NA	Reversible lane	Left-turn restrictions	Lane-use signals and variable message sign	NA	NA	Span wire	Static signs
NA	NA	NA	Reversible lane	None	Lane-use signals and variable message signs	24x24 in (signals); 30x42 in (signs)	10.0	Mastarm	Overhead signs at exit only
17.7	31.5	15.8	Reversible lane	Lane-use control	Lane-use signals	12x12 in	5.4	Span wire	None
NA	NA	NA	Painted left-turn channelization	NA	BUSES ONLY sign; lane-use signals over three lanes	NA	NA	Span wire	NA

during offpeak periods. During peak periods, the two center lanes alternate as two-way left-turn lanes. On Nicholasville Road, the center lane operates as a two-way left-turn lane during offpeak periods. However, during peak periods, only the one outside lane carries through traffic while the adjacent lane is used for two-way left turns.

Accident Analysis

Accident data furnished by officials of the jurisdictions visited included police accident reports, computer-generated accident files and summaries, and manually tabulated accident information. A comparative evaluation was conducted to determine if accident rates for the study sites were significantly different from rates for other urban highways where RF2WLTL's were not in use. Table 2 summarizes accident data from 11 of the RF2WLTL study sites and from 4 studies of urban sites. (*4–7*)

None of the average accident rates for the four urban sites differs significantly at the 0.05 level from the rate for the RF2WLTL sites. Overall, when using Kendall's combination test method (*8*), the average accident rates for RF2WLTL sites are not higher or lower at the 0.05 level than rates for other urban roadways with conventional two-way left-turn lanes.

Driver Information Requirements

Each of the existing RF2WLTL sites was reviewed to determine how well permissive and/or restrictive use information was being provided to the driver. An RF2WLTL site should provide applicable information before the section begins, at the entrance to the section, through the section, and at the end of the section. A worksheet was prepared detailing the lane configuration, delineation, signs, and signals used sequentially at each existing RF2WLTL site (fig. 10). Except on the through portion, few existing sites provide all needed driver information.

Preliminary Laboratory Experiment

A preliminary laboratory experiment was conducted to determine driver understanding of the abstract and contextual meaning of and preference for the symbols and markings being used at RF2WLTL sites. Thirty-two test subjects were shown slides of drawings of a five-lane suburban arterial with overlays of overhead symbols and lane delineation (see display art). The symbol meaning results are shown in table 3, and delineation meaning results are shown in table 4.

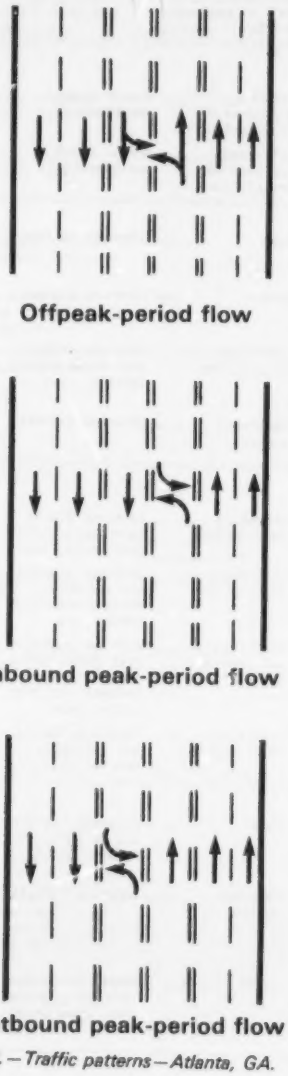


Figure 8.—Traffic patterns—Atlanta, GA.

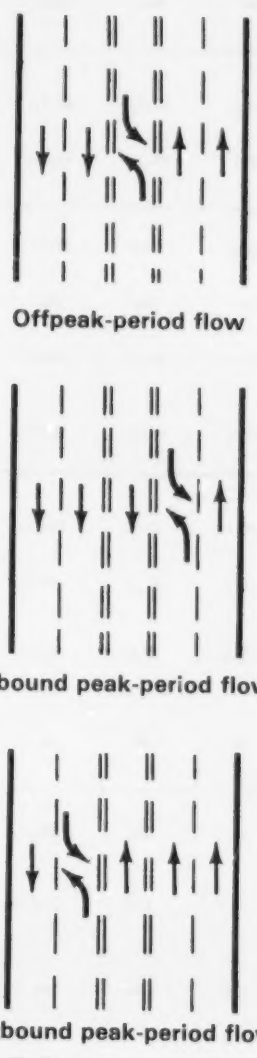


Figure 9.—Traffic patterns—Lexington, KY.

Table 2.—Comparison of accident rates (4–7)

Kind of control	Number of sites	Average accident rate[1]	Standard deviation	t-statistic[2]	p two-tail
Reversible flow two-way left-turn lane	11	9.4	4.0	–	–
Urban multilane undivided sites in 19 cities	2,496	8.6	10.8	0.65	0.53
Two-way left-turn sites:					
North Carolina	13	7.4	3.7	1.28	0.22
Texas	62	11.4	7.3	1.33	0.20
Virginia	17	6.3	4.3	1.90	0.07

[1] Accident rate = accidents per million vehicle miles.
[2] t-test results obtained by comparing the reversible flow two-way left-turn site with the other control types for $p > 0.05$.

1 mi = 1.6 km

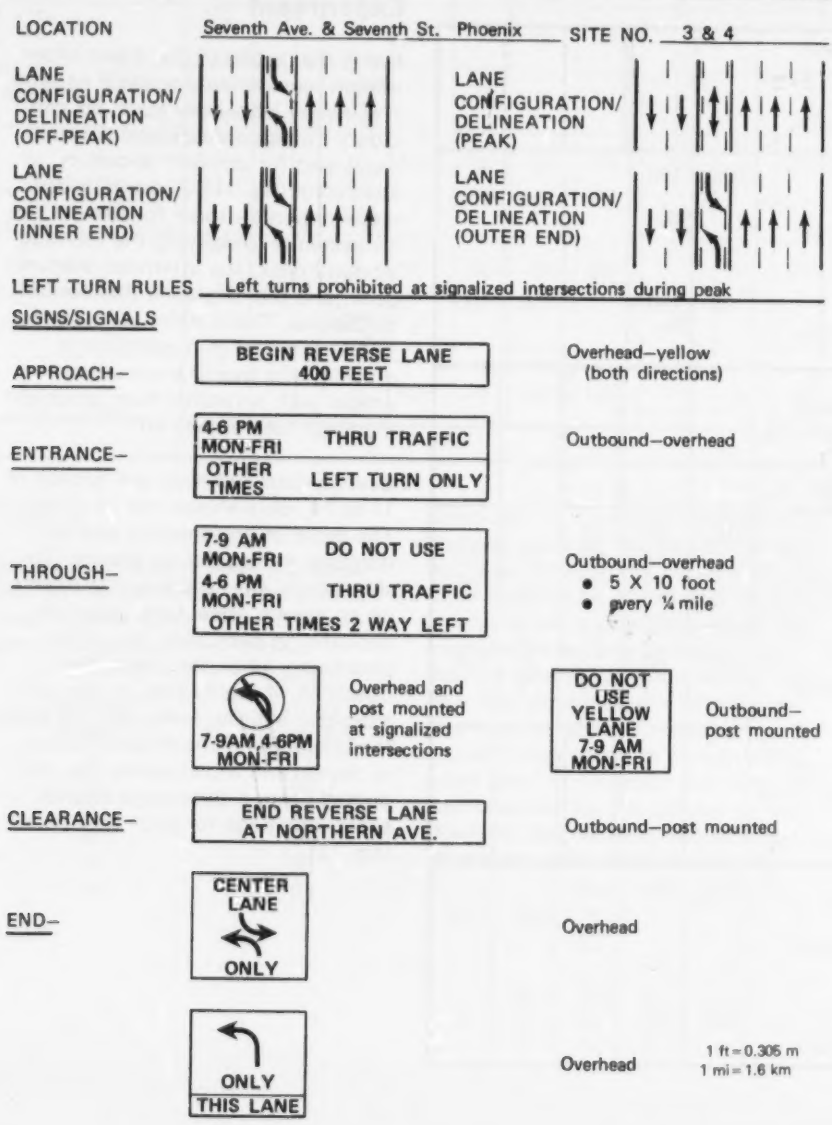


Figure 10.—Example of RF2WLTL facility information worksheet.

All of the test subjects understood the meaning of permissive green arrows and restrictive red X's. However, no subject identified the yellow X as meaning a left-turn lane. The two-way left-turn arrows were identified by 38 percent (when steady) and by 41 percent (when flashing) as a left-turn symbol. Clearly, the two-way left-turn arrows have the best inherent meaning. The delineation test results indicated that subjects understood the reversible flow lane markings better than the other markings presented. The overhead signal symbols were tested in relation to lane position. The two-way left-turn arrows were found to be much more effective than the yellow X in indicating a two-way left-turn lane (table 5).

After the meaning tests were completed, the operation of the RF2WLTL was explained to the subjects. A preference test was administered. Subjects preferred the two-way left-turn arrows 10 to 1 over the yellow X as a symbol for two-way left turns.

Table 3.—Symbol meaning test results—percent subject responses

Response to "What does this lane control signal mean?"	Lane control signal: Green ↓ Steady	Green ↓ Flashing	Red X Steady	Red X Flashing	Yellow ↓ Steady	Yellow ↓ Flashing	Yellow X Steady	Yellow X Flashing	White Steady	White Flashing
Do not use this lane			100	100			84	87	3	6
Use this lane for through travel	100	100			81	84				
Use this lane for left turns									38	41
Use this lane for right turns										
Don't know					19	16	16	13	59	53
Total	100	100	100	100	100	100	100	100	100	100

Table 4.--Roadway marking test--percent subject responses

QUESTION	Response \ Lane Marking						
Which lanes may have traffic traveling toward you?	Yes	100	100				
	No			100	100	100	
	Don't know						
Which lane may you turn left from?	Yes			100			
	No	100	100		100	100	
	Don't know						
QUESTION	**Response \ Lane Marking**						
Which lanes may have traffic traveling toward you?	Yes	100	94	34			
	No		3	31	97	100	
	Don't know		3	34	3		
Which lane may you turn left from?	Yes		9	69	22		
	No	100	88	12	72	100	
	Don't know		3	19	6		
QUESTION	**Response \ Lane Marking**						
Which lanes may have traffic traveling toward you?	Yes	100	100	41			
	No			31	100	100	
	Don't know			28			
Which lanes may you turn left from?	Yes		3	41	50		
	No	100	91	41	44	100	
	Don't know		6	18	6		

Detailed Laboratory Experiment

Using the results of the driver information requirements analysis and the preliminary laboratory tests, six candidate traffic control systems were developed for detailed laboratory evaluation (fig. 11). Eighteen slides were prepared—three for each of the six systems—displaying the morning inbound peak, the afternoon inbound peak, and the offpeak traffic control conditions. These slides were shown to test subjects as overlays on a drawing of a five-lane suburban arterial with reversible flow pavement markings (see display art).

Seventy-four subjects, in 6 groups of 11 to 14, were shown the 18 slides. The order of presentation was randomized among the six groups. To simulate driving, the subjects selected on an answer sheet lane usage as depicted on each slide. As in the preliminary laboratory tests, the operation of the RF2WLTL was not explained initially. Following the tests, the operation of the RF2WLTL was explained and a preference test conducted using a three-page answer sheet, one page for each time period (fig. 12).

Table 5.--Symbol meaning in relation to lane position--percent subject responses

QUESTION	Which lanes may have traffic traveling toward you?					Which lane may you turn left from?				
Signal / Response	Red X	Red X	Red X	Green ↓	Green ↓	Red X	Red X	Red X	Green ↓	Green ↓
Yes	100	100	100						94	
No				100	100	100	97	97		100
Don't know							3	3	6	
Signal / Response			Green ↓					Green ↓		
Yes	100	100	6					97		
No			94	100	100	97	97		97	97
Don't know						3	3	3	3	3
Signal / Response			Yellow X					Yellow X		
Yes	100	100	59				3	3	66	
No			3	100	100	100	97	50	15	100
Don't know			38					47	19	
Signal / Response			Yellow ↓					Yellow ↓		
Yes	100	100	3					75	13	
No			78	100	100	100	100	0	81	100
Don't know			19					25	6	
Signal / Response			Yellow X flash					Yellow X flash		
Yes	100	100	59					28	44	
No			16	100	100	100	100	31	34	100
Don't know			25					41	22	
Signal / Response			↙					↙		
Yes	100	100	41					81	13	
No			9	100	100	100	100	3	81	100
Don't know			50					16	6	
Signal / Response			↙ only					↙ only		
Yes	100	100	59					88	12	
No			6	100	100	100	100	0	88	100
Don't know			34					12	0	

Results

Correct responses to all of the questions on the candidate systems were combined with preference corroboration and aggregated as follows:

Candidate system	Percent correct responses
I	77
II	83
III	57
IV	56
V	58
VI	63

Candidate II, the system including the flashing two-way left-turn arrow symbol, was shown to be better than all other candidates. Candidates III, IV, V, and VI were essentially equal. An examination by time period of candidate I data showed the yellow X to be a very poor indicator of the correct lane for left turns. Also, the yellow X was found to be confusing when used to designate two-way left-turn lanes during the offpeak period. However, the two-way left-turn arrows were easily understood.

FHWA's Office of Traffic Operations' review of the completed RF2WLTL research (*2*) resulted in proposed MUTCD amendments being published in the "Federal Register" dated March 13, 1985. (*3*) The proposed amendments are summarized as follows:

- Add a new section to provide a static sign system as an acceptable alternate to the preferred (but more costly) lane-use control signals. The sign selected was candidate IV (fig. 11), omitting the word "ALL" from the offpeak section of the sign.
- Require double broken yellow pavement markings on each side of a reversible flow two-way left-turn lane.
- Replace the flashing yellow X signal with the nonflashing symbolic two-way left-turn arrow signal (as shown in fig. 11, candidate II) for two-way left-turn operation. Use a single left-turn arrow signal for one-way left-turn lanes.

Comments on the proposed amendments were received in July 1985 and are under consideration by advisory FHWA organizations.

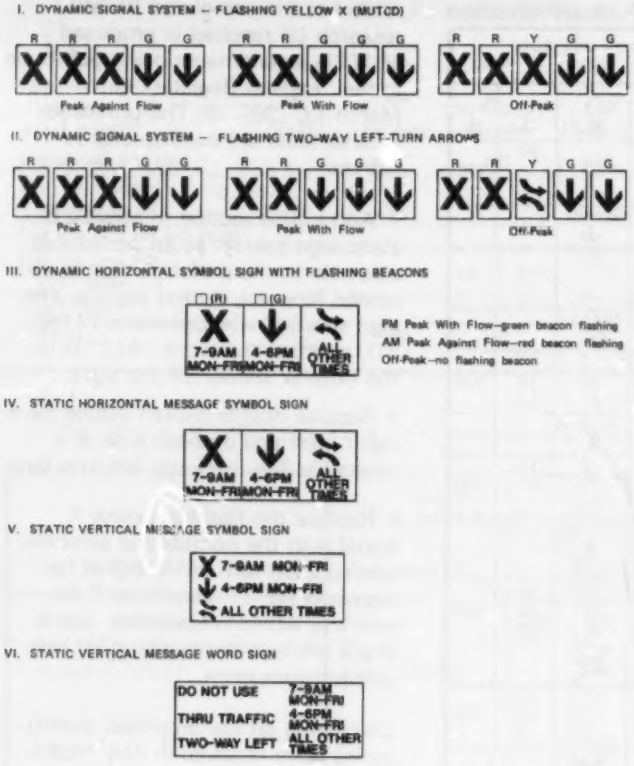


Figure 11. – Candidate RF2WLTL traffic controls developed for detailed laboratory tests.

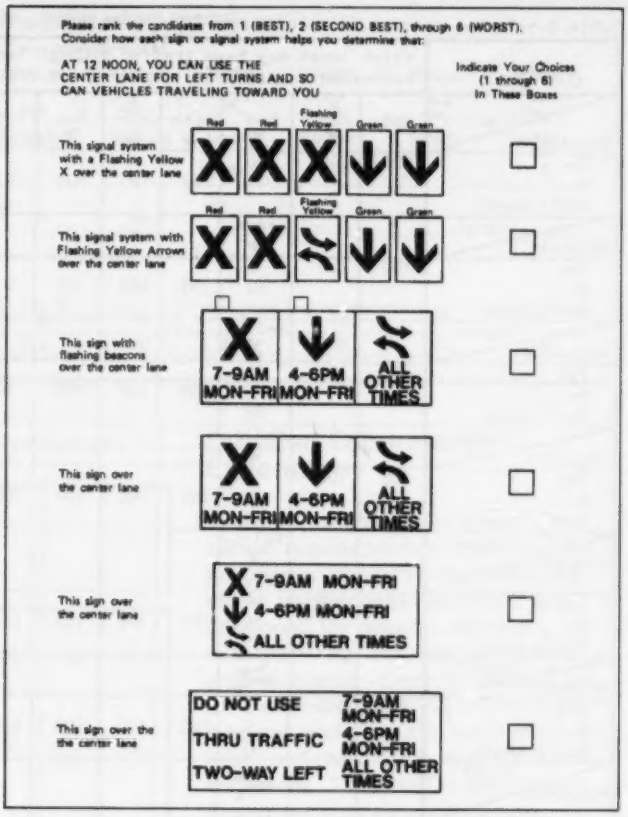

Please rank the candidates from 1 (BEST), 2 (SECOND BEST), through 6 (WORST).
Consider how each sign or signal system helps you determine that:
AT 12 NOON, YOU CAN USE THE CENTER LANE FOR LEFT TURNS AND SO CAN VEHICLES TRAVELING TOWARD YOU
Indicate Your Choices (1 through 6) In These Boxes
This signal system with a Flashing Yellow X over the center lane
This signal system with Flashing Yellow Arrows over the center lane
This sign with flashing beacons over the center lane
This sign over the center lane
This sign over the center lane
This sign over the the center lane
Red Red Flashing Yellow Green Green
7-9AM MON-FRI
4-6PM MON-FRI
ALL OTHER TIMES
DO NOT USE
THRU TRAFFIC
TWO-WAY LEFT

Figure 12. – Example of preference test answer sheet.

REFERENCES

(1) "Manual on Uniform Traffic Control Devices," *Federal Highway Administration,* Washington, DC, 1978.

(2) R.L. Knoblauch, M.R. Parker, Jr., K.H. Tsuchiyama, and J.C. Keegel, "Traffic Control for Reversible Flow Two-Way Left-Turn Lanes," Final Report No. FHWA/RD-85/009 and State-of-the-Art Report No. FHWA/RD-85/010, *Federal Highway Administration,* Washington, DC, October 1984. (Stock Nos. PB 85 129674 and 85 198687.)[2]

(3) "Federal Register," vol. 50, No. 49, Wednesday, Mar. 13, 1985, Washington, DC.

(4) T.K. Datta, M.R. Parker, Jr., and D.A. Randolph, "Analysis of Urban Arterial Road and Street Accident Experience," Report No. FHWA/RD-82/137, *Federal Highway Administration,* Washington, DC, September 1982. (Stock No. PB 85 184448.)

(5) W.F. Babcock and R. Foyle, "Urban Street Design for Traffic and Land Service," Report No. ERSD 110-77-2, *North Carolina State University,* Raleigh, NC, March 1978.

(6) C.M. Walton, T.W. Horne, and W.K. Fung, "Design Criteria for Median Turn Lanes," Research Report No. 212-1F, *Center for Highway Research, University of Texas at Austin,* Austin, TX, March 1978.

(7) M.R. Parker, Jr., "Design Guidelines for Raised and Traversable Medians in Urban Areas," Report No. VHTRC 84-R17, *Virginia Highway and Transportation Research Council,* Charlottesville, VA, December 1983.

(8) M.G. Kendall, "The Advanced Theory of Statistics, Vol. II," *Charles Griffin & Co., Ltd.,* London, England, 1948.

[2]Reports with PB numbers may be purchased from the National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161.

Merton Rosenbaum is a highway research engineer in the Traffic Safety Research Division, Office of Safety and Traffic Operations Research and Development, FHWA. He is involved in research to improve traffic safety and capacity on rural and urban highways. Before joining FHWA in 1961, Mr. Rosenbaum worked for 15 years with the Virginia State Highway Department in highway location and design, traffic and planning, and computer applications.

Integrated Information Systems for Better Data Management

by
Richard A. Richter

Data Needs of Highway and Safety Program Administrators

A highway administrator reads a newspaper headline of a recent traffic accident—TWO KILLED AS CAR HITS BARRIER. The story establishes that the barrier end speared the vehicle and that the driver had been drinking. The administrator wonders, "Who's responsible? The State Police, those involved with the DWI (Driving While Intoxicated) program, or me? Maybe the barrier was poorly maintained or designed. Is the same thing happening frequently throughout the State?"

Responding to the question of responsibility in traffic incidents of this kind is not an unusual task for a highway or safety program administrator. The responses an administrator makes in such cases depend heavily on data gathered by a State and stored in files. To have ready access to these data, an administrator needs an efficient information management system incorporating data collected from many sources and for many purposes. The system needs to be comprehensive, provide quick access to particular aspects of the problem, and provide interrelationships such as rates and trends. However, the more comprehensive the systems are, the more branches, departments, or even agencies within a State that become involved, complicating system maintenance and operation.

In addition, some of the basic requirements for any information system—a common reference system, the ability to screen nonessential information, the ability to be updated easily at regular intervals, and immediate accessibility to users—are difficult to achieve with large, comprehensive information systems using data from several agencies. Therefore, smaller, agency-specific information management systems have been the trend, particularly for highway-related safety information. However, these systems may not be capable of satisfying all needs.

Current State Highway Data Systems

With the emergence of large mainframe computers in the 1960's, many State highway agencies tried to develop efficient, integrated data systems that would serve internal needs as well as respond to outside data inquiries. These efforts generally failed; the cost and personnel required of each group within a highway agency to service an integrated data system were greater than that required to maintain less comprehensive but adequate individual data systems.

The advent of the microcomputer further promoted the concept of individual data systems by facilitating system maintenance and expansion, decreasing data acquisition turnaround time, and allowing administrative control over the files within the individual interest group. Separate individual data systems commonly were developed for

financial, accident, maintenance, and traffic control information; roadway features, bridge, and skid inventories; traffic volume counts; and preconstruction engineering management. Although many of these systems used similar reference systems, the reference systems usually were selected to facilitate data input for the particular subject of interest and therefore were not readily interconnected as they would be in an integrated information system.

As useful as the individual data systems are, they do not allow administrators to make full use of their existing files. Every decision highway administrators make can benefit by ready access to composite records maintained on the various highway systems. For example, a pavement's condition from year to year influences the design of new pavements. Also, data on features at roadway facilities with recurring accidents can be used to establish a pattern of accident cause and to select countermeasures. Finally, the results from guardrail-related accidents can identify the kinds of barriers that may require more frequent replacement. All of these decisions require data from more than one file, frequently accessed by more than one variable, to show trends, rate, severity, or related features. The answer then appears to be an integrated information system (fig. 1).

Such a system typically is accessed through a computer-based management program that uses data from several sources and treats the data as if coming from a single file. These data are linked through a common highway location reference system, usually based on mile points.

Typically all data collected in States are related to some sort of a reference system, the common reference being the number of miles from an easily identified point, milepost, or physical feature on the highway system. It is not always convenient, however, for all data collectors to start measuring from the same point or, in some cases, even use a mile-point system. For example, they may find it more convenient to collect data by relating it to roadway sections of various lengths. Converting all roadway, traffic, and accident files to a common reference system is not easy, but it is a key first step in establishing an integrated information system. (*1*)[1] Then, existing individual data systems may be tied into such a data base management program to upgrade current data accessibility and expand an agency's information system.

Currently, several States have or are developing integrated highway information systems. North Carolina has a system that allows local municipalities to access Statewide files of accidents, roadway features, and traffic characteristics. Utah integrates accident, geographic, and highway information files through a data base management system and allows data access at three levels of detail—executive/manager, technician, and data processing personnel (fig. 2). Idaho and Kansas currently are integrating highway data in cooperation with the Federal Highway Administration (FHWA).

To determine the status of existing State information systems and the degree to which individual files now have been integrated within major systems, the National Cooperative Highway Research Program under its Project 20-5 is developing a synthesis report, "Integrated Highway Information Systems."

Uses of Integrated Data Information Systems

An integrated information system within a highway agency can allow file data to be accessed by roadway features or by location. Often, a highway agency administrator would like to know the number of accidents at luminaire poles, bridge ends, or sign supports and similar roadway features rather than, for example, just knowing which locations are having a particular number of accidents.

A highway agency's information system also can be used to develop accident rates for various roadway features. Raw numbers of accidents at a particular location mean very little unless they are considered in relation to the traffic volumes or some other measure of exposure. An integrated information system can draw upon traffic, accident, and roadway feature data and store them in a single file. Accident rates for a specific feature then can be developed easily by straightforward computer calculations. Examples of data that can be developed are accident rates at all bridge ends, accident rates on roadways with shoulders of a specified width, or accident rates on roadways with a designated skid number.

Another feature of an integrated information system is the ability to specify particular data levels in the output—for example, fatal accidents on all bridges with an average daily traffic (ADT) volume less than 1,000 vehicles per day and having roadway widths of 22 ft (6.7 m) or less. By controlling data variables and determining their interrelationships, the highway administrator can determine how highway improvements are changing accident patterns and can rank accident countermeasures by cost-effectiveness.

Even without all of the agency's files or all related safety information, a highway agency's integrated information system can help in evaluating the safety effectiveness of highway improvements. Ideally, accident countermeasure effectiveness is determined by comparing an improved site with a similar but unimproved control site. It is difficult to locate two sites identical in geometrics, traffic, and hazardousness without using an integrated information system. With an integrated information system, however, the characteristics of the improved site can be described and a file search can be conducted on the basis of these characteristics. Even if a control site cannot be located, the average accident rate from a composite group of similar sites will provide a valid basis for comparison.

[1]Italic numbers in parentheses identify references on page 14.

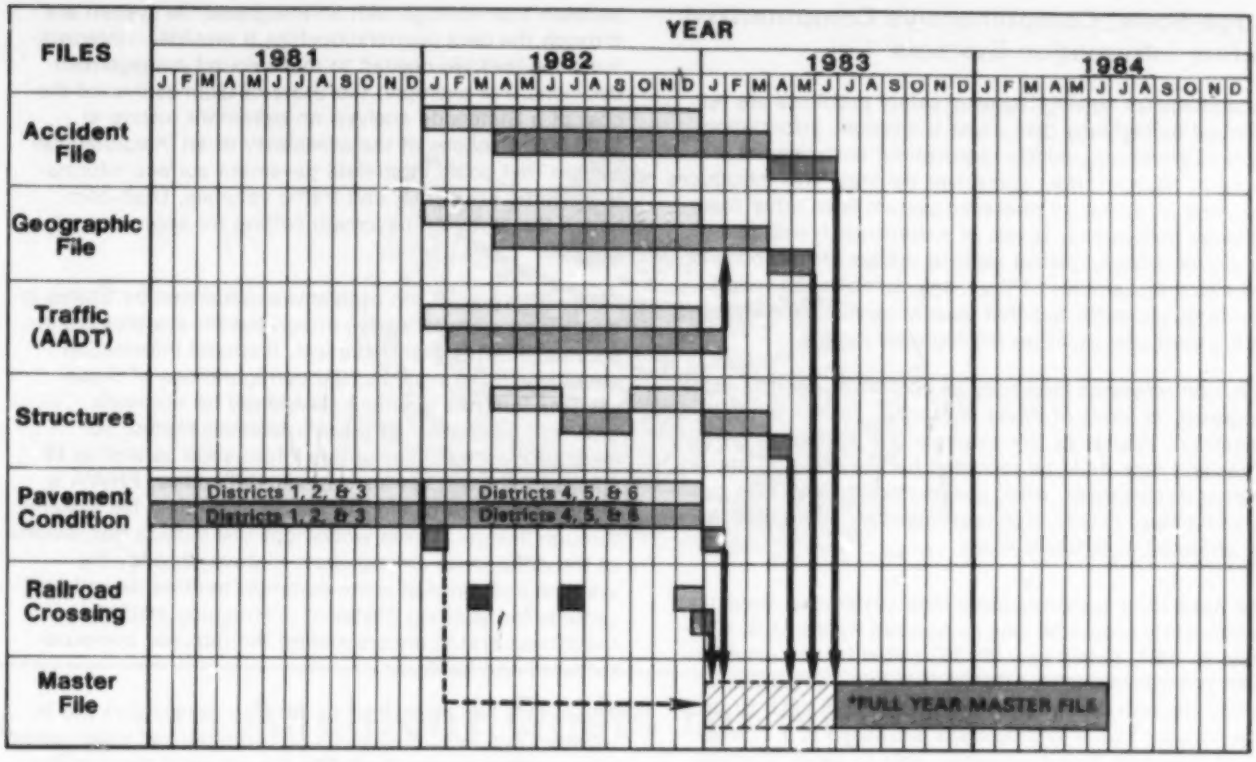


Figure 1.—Integrated information system data collection and file development cycle.

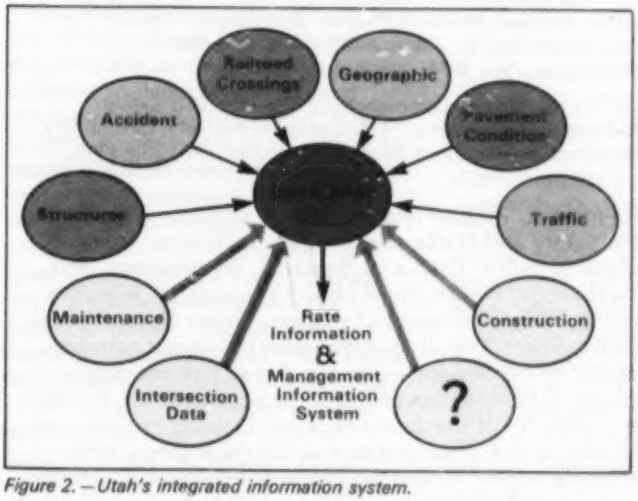


Figure 2.—Utah's integrated information system.

Another useful feature of an integrated information system is that it permits the depth of detail to be varied. Not all file users have a need for the same depth and detail of information. For example, if an administrator wants to know about accidents that occur at bridge ends on a particular highway route, the file system can sort through data on all accidents that occur in the State with related details and select the bridge end accidents. With an integrated file system, the user can have the computer select the route, the locations (bridge ends), the number of accidents, the bridge width, the approach width, whether or not the approach guardrail is connected to the bridge rail, and other pertinent details.

An integrated file system also can be used to monitor the effectiveness of a particular program such as upgrading with a new kind of barrier terminal. For example, an integrated file report can be programmed to search the entire State system for barrier terminals and print, on a monthly basis, the locations, the accident experience, the roadway widths, the prevailing traffic volumes, speed, and other related factors.

Large-Scale, Comprehensive Computerized Safety Information Systems

Data needs for solving highway safety problems are not satisfied by highway data alone but require information such as driver and vehicle registration, enforcement records, court records, and driver training. This introduces the need for common reference system links other than highway mile points. Levels of enforcement, accident history of drivers, relative skills of drivers, or reliability of vehicles are examples of the many variables that contribute to accidents but that usually cannot be associated with a particular point on the highway system.

Common reference links may be accidents, specific safety programs, or kinds of driver violations. Each link has its limitations. Accidents, for example, are temporary conditions, and data must be recorded before items of interest change or disappear. Also, specific safety programs can vary in scope. Finally, violations can vary as regulations are enforced at different levels.

The need for a comprehensive data system for managing traffic safety programs was recognized by the U.S. Congress in 1984. Public Law 98-363 called for the establishment or improvement of Comprehensive Computerized Safety Recordkeeping Systems (CCSRS) in each State. The nature of such systems was discussed at a Transportation Research Board workshop held in Airlie, Virginia, May 6-8, 1985. (*2*) Nine principal applications were considered as being served by a CCSRS—identification of high-accident locations, identification of hazardous roadway elements, development of accident surrogates, selective traffic law enforcement, traffic enforcement planning, driver improvement programs, monitoring of court proceedings, monitoring designated truck routes, and evaluation of highway safety projects and programs. The States of Washington and Texas currently are planning large CCSRS's. As current activities of the National Highway Traffic Safety Administration and the Transportation Research Board develop, new insights into highway safety data management can be expected.

The need for large-scale, comprehensive information systems that integrate all highway safety data is apparent, even though there is much value and more immediate application in managing data for many uses through an intermediate-level integrated system. The potential applications and uses of data from integrated information systems, whether large-scale or intermediate-scale, are unlimited.

Looking Ahead

FHWA's Offices of Research, Development, and Technology are supporting both ongoing contracts and planned activities with State highway agencies to develop greater data management capabilities. FHWA expects that transferring state-of-the-art computerized file system technology to States not presently using such technology can save funds through better, more informed management decisions.

The collection of traffic volume data, feature inventories, and roadway conditions is very expensive, yet necessary, because cost-savings with an integrated file system are through the data interrelationships it provides—interrelationships that are needed to make sound management decisions. For example, the State of Utah estimated the cost of a Statewide analysis on pavement rutting at $160,000. Because of the availability of an integrated file system that could interrelate pavement surface information, traffic accidents, and traffic volumes, Utah completed the study on pavement rutting for approximately $18,000.[2]

Although many of the problems experienced by States in developing comprehensive integrated file systems are institutional rather than technical, firsthand information about operating systems, the configurations of those systems, and the solutions developed for common technical problems can assist interested States. To facilitate dissemination of this information as well as to address the expected institutional difficulties, FHWA is planning a series of workshops on expanding file systems through linkage. These workshops will include discussions of the differences among State highway agency file systems and develop some common treatments and procedures for assisting States in overcoming institutional roadblocks and in understanding the required computer software and hardware.

This article has attempted to put into perspective the integrated and individual levels of computerized information management systems, identify the potential the systems have for those not familiar with such systems, and suggest to States a willingness by FHWA to assist States with the file system technology needed to update their file systems. Top level support from highway agency management is needed to make such comprehensive highway information systems a reality.

REFERENCES

(*1*) "Highway Location Reference Methods," National Cooperative Highway Research Program Synthesis of Highway Practices Report No. 21, *Transportation Research Board,* Washington, DC, 1974.

(*2*) "Introduction to Comprehensive Computerized Safety Recordkeeping Systems," Transportation Research Circular 293, *Transportation Research Board,* Washington, DC, July 1985.

Richard A. Richter is a supervisory highway engineer in the Safety and Traffic Implementation Division, Office of Implementation, Offices of Research, Development, and Technology, FHWA. He is project manager for FCP Project 1Z, "Implementation of Highway Safety Research and Development," which includes several contract activities related to the development of improved highway safety-related data collection and data management. Mr. Richter is a graduate of the Junior Engineer Training Program and previously was employed as a structural engineer with FHWA's Region 15 and the Office of Engineering, a traffic engineer with the Wyoming Highway Department, and a safety standards engineer with FHWA's Office of Highway Safety.

[2] "Rut Depth/Pavement Condition Accident Relationship Study," unpublished report for the Federal Highway Administration, September 1985.

Accident Costs for Highway Safety Decisionmaking

by
Brenda C. Kragh, Ted R. Miller, and Kenneth A. Reinert

Introduction

Important advances are occurring in the field of accident costs. In these budget-conscious days of less money available to decrease the hazards resulting from our fast-paced, mobile society, it is increasingly important to spend available money on the most useful safety measures. To choose the best safety measures, the common denominator—the dollar—is used to compare the costs to implement a safety measure with the expected benefit. Because the highway community uses the number of accidents eliminated or made less severe by a countermeasure as the yardstick for benefits, the dollar amount placed on different kinds of accidents is crucial in spending tax dollars wisely. Highway professionals are no longer satisfied with accepting accident cost numbers routinely updated from an obsolete or undocumented methodology and published as a principal source of information.

Today, few engineers or even economists who specialize in accident costs agree on both the components of accident costs and how to collect the pieces of information. Because of this, in 1982 the Office of Safety and Traffic Operations Research and Development in the Federal Highway Administration's (FHWA) Offices of Research, Development, and Technology initiated research to review and study the basis of accident costs. (*1*)[1] The objectives of the study were to review the differing accident cost numbers and methodological approaches used and to develop, present, and explain updated accident cost numbers. Also, several of the more popularly used accident cost numbers were converted to a common base year (1980) for comparative purposes.

This article describes the results of the FHWA study and suggests accident costs for use by the States and others in determining how best to spend tax dollars to get the most from our highway safety program. Also discussed are the components of accident costs and some factors that influence how the numbers are determined.

[1]Italic numbers in parentheses identify references on page 20.

Accident Classifications

Valuing accident costs in dollars requires some measure of accident severity. Some States keep only simple records, classifying accidents into fatal, serious injury, and minor injury. In the highway community, motor vehicle accidents traditionally have been classified as fatal; A, B, or C injury; or property damage only (PDO) (table 1). (*2*) The American Association for Automotive Medicine developed a more definitive way to classify accidents—the Maximum Abbreviated Injury Scale (MAIS) (table 2). (*1*) This scale is used by a few States and by the U.S. Department of Transportation, which uses the traditional A-B-C classification system as well.

Table 1.—A-B-C injury classification (*2*)

Code	Injury severity level	Representative injuries
F-type	Fatal injury:	A fatal injury is any injury that results in death (within 90 days of occurrence).
A-type	Incapacitating injury:	An incapacitating injury is any injury, other than a fatal injury, which prevents the injured person from walking, driving, or normally continuing the activities (s)he was capable of performing before the injury occurred.
	Inclusions:	Severe lacerations, broken or distorted limbs, skull or chest injuries, abdominal injuries, unconscious at or when taken from the accident scene; unable to leave accident scene without assistance. And others.
	Exclusions:	Momentary unconsciousness. And others.
B-type	Nonincapacitating evident injury:	A nonincapacitating evident injury is any injury, other than a fatal injury or an incapacitating injury, which is evident to observers at the scene of the accident in which the injury occurred.
	Inclusions:	Lump on head, abrasions, bruises, minor lacerations. And others.
	Exclusions:	Limping (the injury cannot be seen). And others.
C-type	Possible injury:	A possible injury is any injury reported or claimed which is not a fatal injury, incapacitating injury, or nonincapacitating evident injury.
	Inclusions:	Momentary unconsciousness, claim of injuries not evident, limping, complaint of pain, nausea, hysteria. And others.
PDO-type	Damage:	Damage is harm to property that reduces the monetary value of that property.
	Inclusions:	Harm to wild animals, or birds, which have monetary value. And others.
	Exclusions:	Harm to wild animals, or birds, which have no monetary value; harm to a snowbank unless, for example, additional snow removal costs are incurred because of the harm; mechanical failure during normal operation, such as tire blowout, broken fan belt, or broken axle. And others.

Components of Accident Costs

Most experts agree that accident costs are composed of direct costs and indirect costs, but there is little agreement as to what constitutes these two costs, particularly the indirect costs.

Direct accident costs

Direct accident costs are the costs of goods and services produced and consumed as a result of accidents. Examples of direct costs cited in the FHWA study were as follows:

- Property damage.
- Emergency medical and transportation service costs.
- Medical treatment costs—emergency room, hospitalization, doctor/surgeon, follow-on care, home modification, etc.
- Legal and court costs.

These costs and others are added together as one portion of accident costs.

Indirect accident costs

Indirect accident costs value all changes and irretrievable losses experienced by people involved in accidents and by society. These changes include intangible aspects of life such as pain and suffering, tangible items such as administrative work performed by service-oriented institutions, or the cost of goods and services the individual(s) now will not be able to produce or perform because of the accident.

The following four indirect cost categories were cited in the FHWA study:

- Social mechanism.
- Human capital.
- Psychosocial deterioration.
- Value of life and safety.

Social mechanism costs

Social mechanism costs stem from the multitude of work and paperwork generated when a person dies or is injured in a motor vehicle accident. The costs for personnel in police and fire departments; insurance, welfare, and public assistance agencies; highway departments; coroners' offices; and others to complete and process forms and perform other tasks after an accident occurs become significant when all accidents are considered. However, these costs are not easily determined. Each agency mentioned above is responsible for more than just actions related to motor vehicle accidents. Thus,

Table 2.—Maximum Abbreviated Injury Scale (*1*)

AIS code	Injury severity level	Representative injuries
1	Minor injury	Superficial abrasion or laceration of skin; digit sprain; first-degree burn; head trauma with headache or dizziness (no other neurological signs).
2	Moderate injury	Major abrasion or laceration of skin; cerebral concussion (unconscious less than 15 minutes); finger or toe crush/amputation; closed pelvic fracture with or without dislocation.
3	Serious injury	Major nerve laceration; multiple rib fracture (but without flail chest); abdominal organ contusion; hand, foot, or arm crush/amputation.
4	Severe injury	Spleen rupture; leg crush; chestwall perforation; cerebral concussion with other neurological signs (unconscious less than 24 hours).
5	Critical injury	Spinal cord injury (with cord transection); extensive second- or third-degree burns; cerebral concussion with severe neurological signs (unconscious more than 24 hours).
6	Maximum injury (currently untreatable, immediately fatal)	Decapitation; torso transection; massively crushed chest.

determining how much time and expense each agency devotes solely to motor vehicle accidents is difficult. In the FHWA study, social mechanism costs were estimated for police, fire department, and coroner/medical examiner services; insurance administration; and welfare and public assistance administration. However, State motor vehicle agency administration and State and local highway department costs could not be satisfactorily estimated with the available data.

Human capital costs

Human capital costs reflect the work the injured or dead person can no longer perform either in the short- or long-term. This work could be for an employer, the family, or for society in general. Duties outside the workplace, such as household chores and volunteer activities, also may be affected. Human capital costs also include reduced abilities to work. For example, a surgeon whose manual dexterity is affected by a motor vehicle accident still can be a doctor in another capacity—just not a surgeon. Consequently, the surgeon's earnings may be reduced.

Psychosocial deterioration

Psychosocial deterioration evaluates changes in the quality of life that are overlooked in the human capital cost category. Intangible items such as mental anguish or chronic pain; family and marital erosion; drug/alcohol abuse; juvenile delinquency; missed/delayed education; overall reduction in quality of life; and loss of contact with friends, family, and community are harder to express in dollar values than are the wages used to value some aspects of human capital costs. However, this fact does not diminish the importance of these intangible items.

Value of life and safety

The value individuals place on their life and safety reflects their willingness to pay (in money, time, freedom, or some other measure of value) to reduce the number or severity of accidents or to ensure continued health and safety.

The many methods for determining willingness-to-pay accident cost numbers or values attempt to determine the dollar value the public is willing to pay to make small changes in the probability of an accident occurring. Such numbers have human capital and psychosocial costs incorporated because each person's responses and actions would be guided to some extent by expected income and quality of life. When accident costs are based on willingness to-pay concepts, program and project choices are more likely to represent the public's desires. (*3, 4*)

Four basic methods have been used to estimate willingness to pay for life and safety: Asking people, deriving figures directly from economic theory, examining salary differences between dangerous and safe jobs, and examining the prices for products such as cars with varying levels of safety or tradeoffs people make between speed and safety. Most literature has focused on the value of life. In a review of the literature on these four methods to determine willingness to pay, it was concluded that the best studies using each method yielded generally consistent values of life between $1 million and $2 million. (*5*)

Approaches for Determining Accident Costs

Human capital approach

The human capital approach for determining accident costs includes direct costs and indirect social mechanism and human capital costs. Over the years, a major shift has occurred in the way human capital costs are determined. For a brief time during the 1960's, human capital minus consumption was an accepted method. This involved subtracting the amount that would be consumed in goods and services in an individual's remaining lifetime from the human capital the individual would supply. By the mid-1960's, there were criticisms of removing consumption. Today, most economists do not feel that the human-capital-minus-consumption method is appropriate to determine human capital costs. However, because the method was popular when the National Safety Council first generated its accident costs, the Council adopted the method. The method remains within the base numbers underlying the Council's annual updates of accident costs, which are used by many analysts in State highway agencies. (*6*)

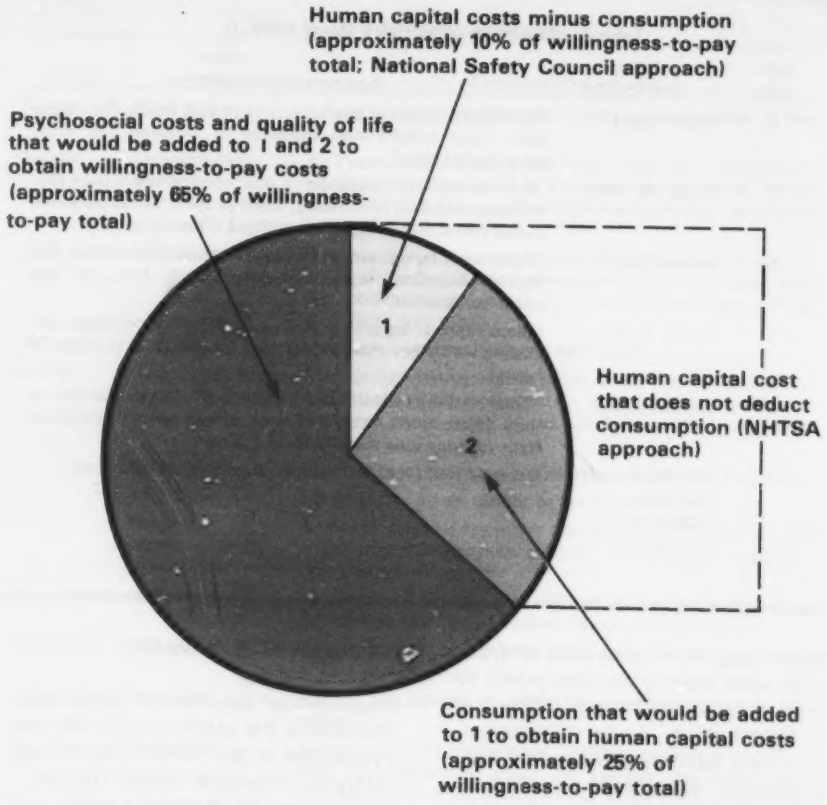

Human capital costs minus consumption (approximately 10% of willingness-to-pay total; National Safety Council approach)
Psychosocial costs and quality of life that would be added to 1 and 2 to obtain willingness-to-pay costs (approximately 65% of willingness-to-pay total)
1
2
Human capital cost that does not deduct consumption (NHTSA approach)
Consumption that would be added to 1 to obtain human capital costs (approximately 25% of willingness-to-pay total)

Figure 1.—Comparison of accident costs based on different approaches, where willingness to pay is the full circle.

As shown in figure 1, the human capital approach that does not deduct consumption (used by the National Highway Traffic Safety Administration [NHTSA]) generates cost figures approximately 2½ times larger than that of the National Safety Council. Such a magnitude of difference in a major component of accident costs greatly impacts total accident costs. The change in accident costs, in turn, would affect the determination of benefits in a benefit-cost analysis and could cause a countermeasure originally classified as not cost-beneficial to be classified as cost-beneficial.

The human capital approach puts a dollar value on death, and this dollar value only considers lost productivity. This approach does not consider the intangibles offered to society such as supportiveness, helpfulness, encouragement, and happiness, which also are part of a person's worth. Basing the approach on dollar values for lost productivity raises the issue of equal pay for equal work. Should women and minorities be valued less because often they earn less than men? Should the elderly have almost no value because of their limited productive years ahead? Are children, because they have nonproductive years before they join the workforce, valued less because their productive years must be averaged over their nonproductive years? Using the human capital approach implies that these groups, because of lower productivity values, have less value to society. The desireability of an accident cost approach that places low values on these groups is questionable. Furthermore, the human capital approach does not value any loss in quality of life (for example, mobility) or pain and suffering that are experienced both during recuperation from an accident and possibly later in life.

Willingness-to-pay approach

For comparison, table 3 shows accident costs computed using the human capital approach and the willingness-to-pay approach. The accident costs based on the human capital approach are derived from information from two documents representing the best sources in this area. (*7, 8*) Unlike these sources, table 3 not only shows costs for each person or vehicle involved—that is, for each incident—but also costs per accident. The estimated costs per accident were based on data from NHTSA's National Accident Sampling System (NASS) on the number and severity of incidents per accident.

The willingness-to-pay accident and incident cost figures generated from the findings of the FHWA study and presented in table 3 include the same values for direct costs and the indirect social mechanism costs as in the human capital costs. They also include life values estimated using a methodology (*9*) that was extended to permit valuation of nonfatal injuries. (*5*)

The willingness-to-pay costs in table 3 are conservative. Economists at the Occupational Safety and Health Administration (OSHA) support using $3.5 million (in 1982 dollars) as the value of a life for regulatory justification. (*10*) The Office of Management and Budget (OMB) supports a $1 million value of life figure (*10*), which is very close to what this article suggests. Subsequently, OSHA and OMB compromised on a value of $2 million.

The Choice of Accident Costs Makes a Difference

Even the conservative willingness-to-pay figures of table 3 are higher than those used by most highway analysts in benefit-cost analyses, suggesting that benefits are being undervalued and justifiable projects are being found unjustifiable because of the lower cost figures. Also, this means that the most cost-beneficial safety projects sometimes will not be the ones selected for implementation when budgets are limited.

Table 3.—Cost per accident and per incident for a variety of accident severity kinds as derived by the willingness-to-pay approach and the human capital approach[1]

Severity by most severe injury	Willingness-to-pay approach		Human capital approach[2]	
	Cost per incident[3]	Cost per accident[3]	Cost per incident	Cost per accident
	Dollars	*Dollars*	*Dollars*	*Dollars*
Fatal	1,156,164	1,305,116	436,521	500,159
Injury	7,108	9,783	5,402	7,361
MAIS injury scale				
MAIS 5 injury	561,849	NC[4]	301,089	NC
MAIS 4 injury	115,254	NC	60,746	NC
MAIS 3 injury	16,592	NC	12,990	NC
MAIS 2 injury	6,705	NC	3,466	NC
MAIS 1 injury	3,015	4,388	2,888	4,203
A-B-C injury scale				
A injury	28,920	36,525	16,508	21,955
B injury	7,720	12,320	5,328	8,499
C injury	3,553	6,682	3,071	5,233
Property damage only	1,070	1,830	1,070	1,830
Average	3,457	3,924	2,538	2,821

[1] All calculations are based on a 5-percent discount rate and are expressed in 1984 dollars.
[2] Includes consumption.
[3] Includes income taxes lost to society and individual's willingness to pay to avoid death and injury.
[4] Not computable from available data.

This is easily illustrated. Consider, for example, a hazardous bridge end on a four-lane highway. A guardrail is proposed to reduce the hazard. Suppose installation and maintenance of the guardrail at this bridge end would cost approximately $5,500 (in 1984 dollars) and that the guardrail would reduce the expected number of injuries by one per year and increase the expected number of property-damage-only accidents by two per year. Using the human capital costs per accident in table 3, the benefit-cost ratio for the guardrail installation would be 0.6—that is, $7,361 − (2 × $1,830)/$5,500—and therefore would not be cost-effective (benefit-cost ratio ≥ 1.0 = cost-effective). Similarly, using the willingness-to-pay costs per accident in table 3, the benefit-cost ratio would be 1.11—that is, $9,783 − (2 × $1,830)/$5,500—and it would be cost-effective to install the guardrail. The different accident cost numbers changed what decision would be recommended.

Summary

How accident cost numbers are derived is important, and which accident cost numbers are used makes a difference in selecting accident countermeasures to implement. Some popular published numbers must not be blindly accepted. The willingness-to-pay numbers recommended in the study discussed in this article ($1.1 million for the value of a life and $1.3 million for the cost of a fatal accident—from table 3) resulted from careful examination of all sides of the major economic issues concerning accident cost derivation. They are conservative for current economic thought, yet they are considerably higher than figures currently used by some highway agencies and are more in line with the OMB/OSHA compromise of $2 million for the value of a life. The choice of numbers to use requires responsible decisionmaking to get the most for the money in terms of benefits for the public. Economically sound accident cost numbers are an essential tool for making responsible decisions.

REFERENCES

(1) Ted R. Miller, Kenneth A. Reinert, and Brooke E. Whiting, "Alternative Approaches to Accident Cost Concepts," Report No. FHWA/RD-83/079, *Federal Highway Administration,* Washington, DC, January 1984 (PB No. 84 196658).[2]

(2) "Manual on Classification of Motor Vehicle Traffic Accidents," Fourth Edition, National Safety Council, ANSI D16.1-1983 Revised, Chicago, IL, Dec. 2, 1983.

(3) Martin J. Bailey, "Reducing Risks to Life," *American Enterprise Institute,* Washington, DC, 1980.

(4) Mark S. Thompson, "Benefit-Cost Analysis for Program Evaluation," *Sage Publication,* Beverly Hills, CA, 1980.

(5) Ted R. Miller et al., "Development of a Value Criteria Methodology for Assessing Highway Systems Cost-Effectiveness," Report No. FHWA/RD-85/086, *Federal Highway Administration,* Washington, DC, May 1985 (PB No. 85 219236).

(6) "National Safety Council Estimating Procedures for the Annual Cost of Accidents," *Statistics Division, National Safety Council,* Chicago, IL, 1974.

(7) Nelson S. Hartunian, Charles N. Smart, and Mark S. Thompson, "The Incidence and Economic Costs of Major Health Impairments," *Insurance Institute for Highway Safety*, Lexington Books, Lexington, MA, 1981.

(8) "The Economic Cost to Society of Motor Vehicle Accidents," *National Highway Traffic Safety Administration, U.S. Department of Transportation,* Washington, DC, 1983.

(9) J. Steven Landefeld and Eugene P. Seskin, "The Economic Value of Life: Linking Theory to Practice," *American Journal of Public Health*, vol. 72, No. 6, June 1982, pp. 555-566.

(10) Pete Earley, "What's a Life Worth?" *The Washington Post Magazine*, June 9, 1985, Washington, DC, pp. 10-13 and 36-41.

Brenda C. Kragh is an economist in the Federal Highway Administration, Office of Safety and Traffic Operations Research and Development, Traffic Safety Research Division. She manages contracts within FCP Project 1K, "Accident and Countermeasure Analysis." Currently, she is involved in work on improved accident costs, microcomputer integrated information and evaluation software, and development of accident surrogates for two-lane rural roads.

Ted R. Miller is an economist and senior research associate at The Urban Institute. Dr. Miller has worked on resource allocation for health and safety programs since 1971. He has been the principal investigator on several FHWA studies including a current contract that will provide improved accident cost estimates in 1988.

Kenneth A. Reinert is a research assistant at the Bureau of Business and Economic Research. He is a graduate student at the University of Maryland, Department of Economics, and provided key input for the FHWA study discussed in this article.

[2]Reports with PB numbers may be purchased from the National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161.

State-of-the-Art Pile Load Test Program for the Third Lake Washington Bridge

by
Suneel N. Vanikar and LeRoy Wilson

Introduction

Washington State Department of Transportation (WSDOT) currently is reconstructing Interstate 90 in the Seattle area to increase traffic carrying capacity and eliminate existing traffic hazards. This reconstruction requires an 8,400-ft (2.6-km) long bridge to be built over Lake Washington at a cost of approximately $96 million. The main part of the bridge will be a floating structure that will cost approximately $64 million. Piers under the approaches to the floating bridge will be located in variable water depths up to 90 ft (27.4 m).

WSDOT geotechnical engineers initially recommended using either 48-in (1.2-m) diameter steel pipe piles or 54-in (1.4-m) diameter prestressed concrete cylinder piles, each with a design load of 300 tons (2.7 MN) (compression), for pier support of the approaches. However, it was felt that higher loads were possible provided they could be verified by load tests. The Federal Highway Administration (FHWA) concurred with WSDOT engineers and FHWA participated in a load test program by providing technical assistance, a mobile pile load test frame for static load testing, and dynamic pile testing equipment (pile analyzer) to monitor the piles during driving.

Reasons for the Load Test Program

The load test program was conducted for two major reasons—first, to determine if the allowable pile design load in compression could be increased, thereby saving considerable costs, and second, to evaluate pile driveability. Tension load tests were performed to verify the uplift capacity of piles. Because the subsurface soil profile at the bridge site consisted of a shallow deposit of loose silty sand and sandy silt underlain by very dense sandy gravel and fine-to-coarse sand deposit (glacial till), there was concern that the closed-ended piles might not penetrate deeply enough into the very dense till to provide sufficient uplift capacity. Also, pile driveability was of vital importance for the large-diameter closed-ended piles because they would be difficult to drive in the dense glacial till and might be susceptible to damage because of the large-size hammer required for driving.

Features of the Load Test Program

Two 48-in (1.2-m) diameter closed-ended pipe piles with specially designed tip extensions were load tested, one on each side of the lake, at locations where the lake was about 85 ft (25.9 m) deep (fig. 1). The piles were 160 ft (48.8 m) long and ¾ in (19 mm) thick. The pile wall thickness of ¾ in (19 mm) was determined necessary to keep the driving stresses within allowable limits based on wave equation analysis. Closed-ended load test piles were chosen to mobilize the tremendous end bearing capacity available in the very dense glacial till soils, allowing much shorter pile lengths than open-ended piles and thus reducing pile cost. One pile was fitted with a 10-ft (3-m) long fabricated H-shaped tip, and the other pile was fitted with a 10-ft (3-m) long open-ended pipe that was ¾ in (19 mm) thick and 48 in (1.2 m) in diameter. To evaluate the static pile load test, vibrating wire strain gauges and telltale extensometer rods were installed inside each test pile to provide vital data on the load transfer distribution between the pile and the soil. At each test site, four closed-ended piles 36 in (0.9 m) in diameter, ¾ in (19 mm) thick, and approximately 160 ft (48.8 m) long were used as reaction piles. All of the piles were fabricated in shop and barged full length to the project site.

Wave equation analysis indicated that the minimum hammer energy required to drive the piles would be 90,000 ft·lb (121.5 kJ). The load test piles were monitored during driving with the FHWA pile analyzer. The analyzer provided the static pile capacity, stresses in the pile during driving, and the hammer energy transferred to the pile under each blow.

The compression load test was conducted to a maximum load of 1,000 tons (8.9 MN) using the FHWA mobile pile load test frame, and the tension tests were performed until the pile uplift capacity was exceeded.

Results of the Load Test Program

The compression piles were driven, without damage, using a single-acting steam hammer with a maximum rated energy of 90,000 ft·lb (121.5 kJ). The pile with the H-shaped tip was driven 34 ft (10.3 m) into the lake bed, and the pile with the open-ended pipe tip was driven 16 ft (4.9 m) into the lake bed. The compression load tests for both test piles showed that the ultimate capacity was 1,000 tons (8.9 MN). Using a safety factor of 2, an allowable design load of 500 tons (4.4 MN) was recommended—significantly more than the initial design load recommendation of 300 tons (2.7 MN).

Figure 1.—Bridge pile load test setup.

The ultimate load capacity predicted by the pile analyzer during driving of the test piles was 780 tons (6.9 MN). Even though the analyzer tended to underestimate the load bearing capacity, it proved to be a valuable tool in monitoring the performance of the pile hammer and in monitoring the driving stresses in the pile.

The load transfer data obtained from the pile instrumentation indicated that the pile capacity was 90 percent in end bearing. This information was used in wave equation analysis for the procuction piles.

The uplift capacity of the pile with the H-shaped tip was exceeded at 250 tons (2.2 MN) of uplift load. The test pile with the open-ended pipe tip was damaged during driving where the pipe attached to the pile and failed under 50 tons (444 kN) of uplift load. Based on this information, WSDOT decided to use a larger H-shaped tip for production piles to provide the required uplift capacity.

The pile driveability of the ¾-in (19-mm) wall piles with an air/steam hammer with a maximum rated energy of 90,000 ft·lb (121.5 kJ) was confirmed. The maximum hammer energy transferred into the pile top, as measured with the pile analyzer, varied from 40,000 to 60,000 ft·lb (54 to 81 kJ). The pile wall thickness of ¾ in (19 mm) proved to be more than adequate. If the wave equation analysis had not been used before the load test to estimate driving stresses, a wall thickness of 1¼ in (32 mm) would have been specified.

Cost savings

The total cost of the load test program was $500,000.[1] Three quantifiable cost savings that resulted from the program are as follows:

- Fewer piles were used as a result of the load test verification of the 500-ton (4.4-MN) design capacity versus the 300-ton (2.7-MN) preliminary design estimate.
- Piles with ¾-in (19-mm) wall thicknesses were used versus piles with 1¼-in (32-mm) wall thicknesses as originally estimated.
- Smaller size pile caps will be required at each pier as a result of using fewer piles.

Another major cost savings that was realized, although not easily quantifiable, was the reduced pile driving prices that resulted from making all of the load test pile driveability information available to prospective construction bidders during the project advertisement. A net cost savings of approximately $5 million was realized on this project, providing a very favorable benefit-cost ratio of 10:1.[2]

Summary

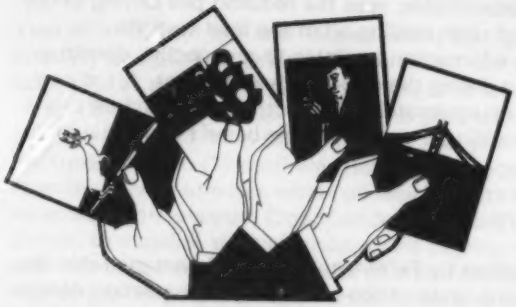
This joint effort by FHWA and WSDOT demonstrates the value of using state-of-the-art structure foundation design and construction methods to provide more cost-effective pile foundations. On large-scale projects, the load test programs should be performed during the design stage rather than during the bridge construction stage because of a greater potential for cost savings. The detailed design of the load test program, good contract specifications, and excellent work by the contractor all contributed to the success of the pile load test program for the Third Lake Washington Bridge.

Suneel N. Vanikar is a geotechnical engineer in the Geotechnical and Materials Branch, Office of Highway Operations, FHWA. He is project manager for Demonstration Project No. 66 on pile foundations and is author of "FHWA Manual on Design and Construction of Driven Pile Foundations." His 21 years' experience includes bridge design and geotechnical engineering.

LeRoy Wilson is a foundation engineer in the Washington State Department of Transportation. He has worked in the Washington State government for 24 years and managed the bridge pile load test program discussed in this article.

[1] L. Wilson, "Pile Load Test at Lake Washington," internal document, Washington State Department of Transportation, Olympia, WA.

[2] Ibid.



Recent Research Reports You Should Know About

The following are brief descriptions of selected reports recently published by the Federal Highway Administration, Offices of Research, Development, and Technology (RD&T). The Office of Engineering and Highway Operations Research and Development (R&D) includes the Structures Division, Pavements Division, and Materials Division. The Office of Safety and Traffic Operations R&D includes the Traffic Systems Division, Safety Design Division, and Traffic Safety Research Division. The reports are available from the source noted at the end of each description.

Requests for items available from the RD&T Report Center should be addressed to:

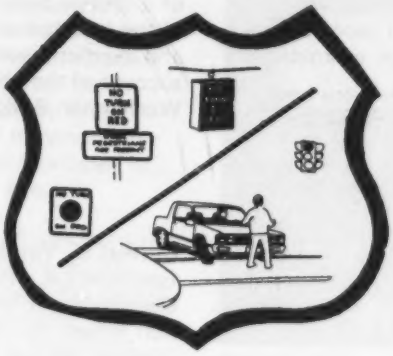
Federal Highway Administration
RD&T Report Center, HRD-11
6300 Georgetown Pike
McLean, VA 22101-2296
Telephone: 703-285-2144

When ordering from the National Technical Information Service (NTIS), use PB number and/or the report number with the report title and address requests to:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

Methods of Increasing Pedestrian Safety at Right-Turn-on-Red Intersections, Report No. FHWA/RD-85/047

by Safety Design Division



The study discussed in this report was conducted to determine current motorist compliance to right-turn-on-red (RTOR) regulations, develop and field test countermeasures for RTOR pedestrian accidents, and develop improved warrants and guidelines for RTOR. Based on data from several cities in the United States, only 3.7 percent of all right-turning drivers violate NO TURN ON RED (NTOR) signs. However, of drivers with an opportunity to turn right on red, 20 percent violated the sign. At RTOR locations, 56.9 percent of motorists do not come to a complete stop before turning right. In comparison, 68.2 percent of motorists do not come to a full stop at stop signs.

Based on conflict and violation data, 30 possible countermeasures were developed for RTOR pedestrian accidents. Six of these countermeasures were field tested, including an offset stop bar, a red ball (symbolic) NTOR sign, a larger 30- x 36-in (762-x 914-mm) NTOR sign, a LOOK FOR TURNING VEHICLES pavement marking, a NTOR WHEN PEDESTRIANS ARE PRESENT sign, and an electronic variable message (blankout) NTOR sign. Several promising applications for the countermeasures were recommended, and current MUTCD guidelines on RTOR prohibition were critiqued. Improved guidelines were recommended based on an analysis of conflicts at 199 intersection approaches.

The report may be purchased from NTIS (PB No. 86 100484).

Pedestrian Trip-Making Characteristics and Exposure Measures, Report No. FHWA/RD-85/074

by Safety Design Division

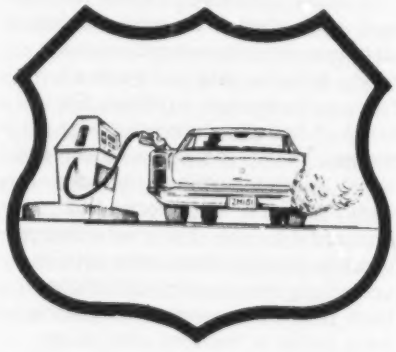
This report discusses a study that identified specific pedestrian trip-making characteristics, developed pedestrian exposure measures, and examined these trip-making characteristics and exposure measures relative to accident information to determine accident rates and the relative hazardousness of various pedestrian characteristics and behaviors.

A large-scale field study was conducted in five standard metropolitan statistical areas in the United States; 1,357 sites were measured, photographed, and described. Volume and activity data were recorded on 612,395 vehicles and 60,906 pedestrians. Also, 20,147 pedestrians were coded by demographic characteristics and behavior.

The report presents data on pedestrian trip-making characteristics and behavior—who walks, where they walk, how they walk (or run), and when they walk. Pedestrian exposure is described in terms of the number of pedestrian-vehicle (PxV) interactions. Exposure data are presented in terms of various pedestrian and site characteristics. Accident rates and relative hazardousness were determined by comparing the exposure data to pedestrian accident data. Accident rates and the relative hazard associated with various site characteristics, pedestrian and vehicle characteristics, and pedestrian and vehicle actions are presented.

The report may be purchased from NTIS (PB No. 86 100039).

Fuel Consumption and Emission Values for Traffic Models, Report No. FHWA/RD-85/053



by Traffic Systems Division

The study described in this report combined laboratory (dynamometer) testing with onroad testing to assess the energy and environmental characteristics of passenger vehicles as they operate in "real-world" conditions. The report documents the methodologies used in the development of fuel consumption and emission characteristics for 15 passenger vehicles representing 64 percent of the 1980–1992 population. Tables and graphs relating vehicular fuel consumption and emissions to speed and acceleration were developed.

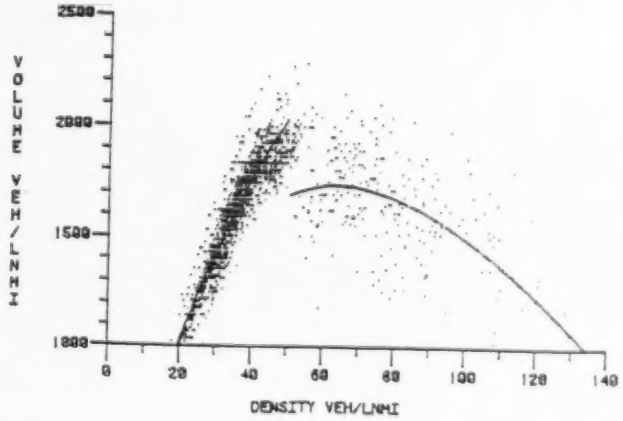
The report may be purchased from NTIS (PB No. 86 143963).

Demand-Responsive Strategies for Interconnected Freeway Ramp Control Systems, Vols. I–III, Report Nos. FHWA/RD-85/109-111

by Traffic Systems Division

These reports present the results of a study to develop a demand-responsive strategy for freeway ramp control. Specifically, surveillance data processing algorithms using the Kalman filter methodology and a ramp metering algorithm using a linear regulator from optimal control theory were developed.

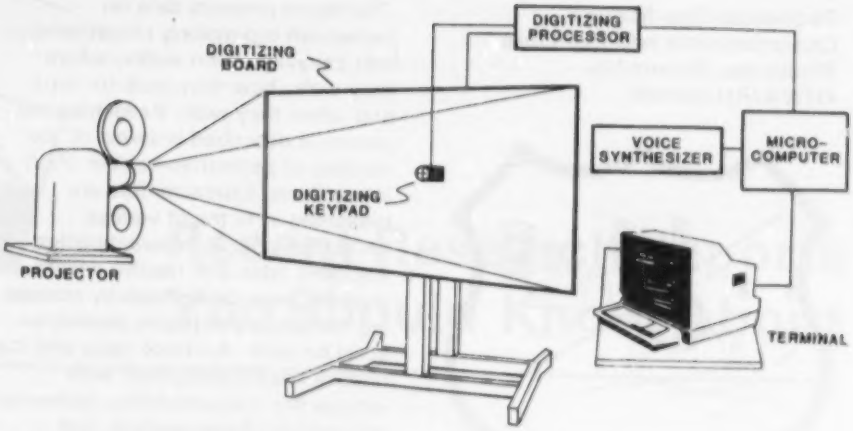
Volume I, **Metering Strategies,** discusses simulation testing of the demand-responsive control strategy developed using the macroscopic simulation program FREFLO. Results show that the regulator provides a demand-responsive control strategy capable of alleviating congestion at various levels of surveillance, effectively manages recurrent congestion by avoiding over-capacity densities, and provides an efficient mechanism for returning the freeway to an uncongested state after an incident.



Volume II, **Program Documentation,** presents the program documentation for the software written to support simulation testing using FREFLO. Software was developed to perform both the freeway surveillance and ramp metering functions necessary for demand-responsive control. The program documentation, in the form of code structure charts and source code listings, includes the software necessary to input the parameters, to perform the online computations, and to perform the offline computations required to operate FREFLO in a ramp metering mode.

Volume III, **Users Guide,** presents information for using the software for simulation testing with FREFLO. The users guide consists of data flow diagrams and sample inputs that should enable a user to run the software. Additionally, a discussion of the integration of the surveillance/control software system with existing hardware to control a real freeway system is included.

The reports may be purchased from NTIS (PB Nos. 86 122462, 86 122470, and 86 122488).



Freeway Data Collection for Studying Vehicle Interactions—Technical Report, Report No. FHWA/RD-85/108, and Appendixes H and I, Report No. FHWA/RD-86/023

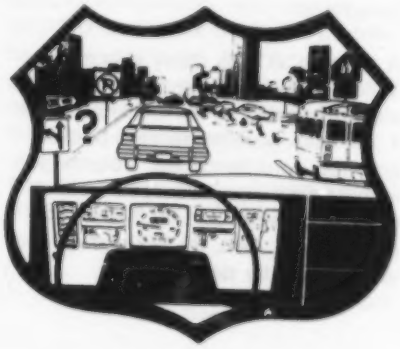
by Traffic Systems Division

The study described in these reports was conducted to develop a series of data sets on microscopic vehicular traffic flow for selected kinds of freeway bottleneck sections. Six kinds of freeway geometry were of interest: Ramp merges, weaving sections, upgrade sections, reduced width sections, lane drops, and horizontal curves. The methodology used to develop these data sets involved digitizing vehicle positions from time-lapse aerial photography for a series of freeway sites under various geometric configurations. These data sets are expected to be useful for both empirical research on freeway traffic flow and for validating freeway simulation models.

Appendixes H and I describe the setup for the digitizing system and present the source code for the computer program.

The reports may be purchased from NTIS (PB Nos. 86 114667 and 86 114675).

Sign Luminance Requirements for Various Background Complexities, Report No. FHWA/RD-85/056



by Traffic Safety Research Division

The Federal standards for luminance of retroreflective materials for traffic signs are acceptance standards; they provide no differentiation in luminance based on driver need. Sign luminance affects sign comprehension, legibility, and conspicuity. This

report describes research to establish, for different levels of scene complexity, luminance levels for conspicuity of yellow diamond warning signs at night. A procedure based on rating sign locations on four subjective scales was found useful for identifying complexity scenes that required signs with different sign luminance levels.

The results clearly support earlier research in demonstrating that the visual complexity of a scene is important in determining nighttime sign luminance requirements.

The report may be purchased from NTIS (PB No. 86 127545).

Screening of Structural Adhesives for Application to Steel Bridges, Report No. FHWA/RD-86/037

by Structures Division

This interim report presents the preliminary findings of a study to determine whether adhesives are durable enough to replace welded connections in highway bridge members in typical bridge environments. The focus of most previous research has been limited to studying the effects of temperature changes on the mechanical properties of bulk specimens and bonded specimens. Although the detrimental effects of water were recognized, few studies attempted to quantify its effect, and no study let the water content in the bulk adhesive equilibrate with the relative humidity of the ambient environment. These environmental effects are addressed in this report.

The results of pilot tests of polymetric materials and screening tests of adhesives are presented. The report also explores the equations needed to analyze the behavior of adhesives using concepts of thermodynamics of elasticity.

The report may be purchased from NTIS (PB No. 86 142601).

Tolerable Movement Criteria for Highway Bridges, Report No. FHWA/RD-85/107

by Materials Division

This report describes a new method that uses a rational set of tolerable movement criteria for designing bridges and their foundations. This new design method emphasizes the optimization of the design of the superstructure and its supporting substructure as a single integrated system offering the best combination of long-term performance and economy. Tolerable movement criteria based on strength and serviceability are presented, in terms of limiting longitudinal angular distortion, horizontal movements of abutments, deck cracking, and bridge vibrations. The supporting data from analytical and field performance studies also are described for steel and concrete bridges.

Limited copies of the report are available from the RD&T Report Center.

Implementation/User Items "how-to-do-it"

The following are brief descriptions of selected items that have been completed recently by State and Federal highway units in cooperation with the Office of Implementation, Offices of Research, Development, and Technology (RD&T), Federal Highway Administration. Some items by others are included when the items are of special interest to highway agencies.

When ordering from the National Technical Information Service (NTIS), use PB number and/or the report number with the report title and address requests to:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

Guidelines for the Administration of Highway Construction Claims, Report Nos. FHWA-TS-85-215/218

by Office of Implementation

Four final reports resulted from a study conducted to alleviate the confusion caused by current methods for settling contractor claims against State highway agencies and the Federal Highway Administration (FHWA) and to recommend new guidelines to reduce the number of claims filed.

The first report, **Highway Construction Contract Claims: Causes and Resolution Practices,** Report No. FHWA-TS-85-215, is a comprehensive investigation of the origin of claims, practices, and procedures in eight selected States.

The second report, **Analysis of FHWA Participation in Highway Construction Claims,** Report No. FHWA-TS-85-216, describes the role of FHWA in the settlement process and presents recommendations for improvement.

The third report, **Comparative Analysis of Time and Schedule Performance on Highway Construction Projects Involving Contract Claims,** Report No. FHWA-TS-85-217, discusses specific aspects of contract administration and claims, especially scheduling and time problems.

The fourth report, **A Synthesis of the Prequalification Procedures of Six State Departments of Transportation,** Report No. FHWA-TS-85-218, examines contractor prequalification practices.

The reports may be purchased from NTIS (PB Nos. 86 122520, 86 122678, 86 122538, and 86 122686).

Portland Cement Concrete Pavement Pulverizing Equipment, Report No. FHWA-TS-85-224

by Office of Implementation

Portland cement concrete (PCC) commonly is broken up using gravity drop hammers, trailer-mounted diesel hammers, spring arm hammers, and vibrating beam breakers. Removal of steel in PCC is a labor-intensive, low-production operation. Breaking and crushing operations need to be improved so that large quantities of coarse aggregate can be produced from PCC. Field operations need to be improved to prevent or reduce the amount of base course contamination.

Considering the condition of pavements in the United States, the current recycling quantities, and the expected growth of recycling, 50 to 100 equipment units will be required in 20 years to break or pulverize PCC pavements. Because funding for new equipment has been slow to develop, Federal and State governments may have to include several large projects in a single contract to provide the volume of work necessary to pay the "front-end" costs for innovative equipment development.

The report may be purchased from NTIS (PB No. 86 123544).

Proceedings, Workshop in Pavement Rehabilitation, Report No. FHWA-TS-84-224

by Office of Implementation

The Workshop in Pavement Rehabilitation, held in Salt Lake City, Utah, September 17-20, 1984, was attended by more than 135 people from the Federal, State, and local governments, as well as industry and academia. This report includes 47 of the 49 papers presented at the workshop.

These proceedings cover most aspects of asphalt concrete pavement and portland cement concrete pavement rehabilitation including recycling, overlay design, relief joints, load transfer, and drainage. Life cycle costs, traffic loading, traffic control, and maintenance were addressed. In addition, national rehabilitation policies, perspectives of industry, and ongoing research are discussed.

The report may be purchased from NTIS (PB No. 85 214260).

Roadway Evaluation Equipment Workshop, Report No. FHWA-TS-85-210

by Office of Implementation

The Roadway Evaluation Equipment Workshop was held September 24-26, 1984, in University Park, Pennsylvania. Recently developed equipment for measuring and evaluating pavement condition was discussed in formal presentations to State transportation personnel and was demonstrated at the Pennsylvania Transportation Institute's research facilities. Testing and calibration methods essential for roadway management systems also were presented, and 24 presentations are included in this report. Among the devices discussed are the Mays ride meter, roughness surveyor, Swedish laser road surface tester, and the falling weight deflectometer.

The report may be purchased from NTIS (PB No. 85 220226).

Proceedings, Tri-Regional Pavement Rehabilitation Conference, Report No. FHWA-TS-84-223

by Office of Implementation

This conference, held May 14-17, 1984, in Oklahoma City, Oklahoma, provided a forum for practicing engineers, administrators, and industry representatives to discuss and demonstrate both proven and the most promising technology available for the evaluation and rehabilitation of pavement systems in the United States.

The agenda included speakers and other participants from 17 States, 3 leading universities, the construction industry, and representatives of companies that manufacture state-of-the-art automated pavement data collection systems, including the latest equipment from other countries. The latest concrete pavement rehabilitation techniques were demonstrated onsite, and several of the latest automated data collection systems were demonstrated and displayed. The papers presented in this report are reprinted from the authors' original papers.

The report may be purchased from NTIS (PB No. 85 183812).

New Research in Progress

The following new research studies reported by FHWA's Offices of Research, Development, and Technology are sponsored in whole or in part with Federal highway funds. For further details on a particular study, please note the kind of study at the end of each description and contact the following: Staff and administrative contract research—*Public Roads* magazine; Highway Planning and Research (HP&R)—performing State highway or transportation department; National Cooperative Highway Research Program (NCHRP)—Program Director, National Cooperative Highway Research Program, Transportation Research Board, 2101 Constitution Avenue, NW., Washington, DC 20418.

FCP Category 1—Highway Design and Operation for Safety

FCP Project 1A: Traffic and Safety Control Devices

Title: Fundamental Studies on Speed Zoning and Control. (FCP No. 31A4054)
Objective: Define realistic speed zoning and develop the traffic engineering tools to derive it by understanding why motorists break speed laws and how they perceive existing speed limits. Conduct controlled speed limit trials to determine the basic relation between changes in speed limits and changes in accident risk. Emphasize developing speed zoning and controls that promote voluntary compliance and provide the best traffic service for a given set of conditions. Examine absolute and prima facia speed limits, legal issues, public acceptance, and cost/performance tradeoffs.
Performing Organization: Martin Parker and Associates, Canton, MI 48187
Expected Completion Date: April 1989
Estimated Cost: $50,000 (FHWA Administrative Contract)

FCP Project 1P: Night Visibility

Title: Tradeoff Between Delineation and Lighting on Freeways. (FCP No. 31P2024)
Objective: Determine freeway interchanges that require lighting and those that can be treated effectively with improved delineation techniques such as raised pavement markers. Conduct driver performance studies to develop cost-effectiveness information for both clear and wet weather.
Performing Organization: IFR Applications, State College, PA 16801
Expected Completion Date: January 1988
Estimated Cost: $233,510 (FHWA Administrative Contract)

FCP Project 1Z: Implementation of Safety R&D

Title: Speed Control Through Work Zones—Technique Evaluation. (FCP No. 31ZA318)
Objective: Determine the long-term speed effects of innovative flagging, law enforcement, variable message signing, and roadway narrowing when used to control traffic in highway work zones. Develop a brief guideline on work zone speed control for incorporation in the "Traffic Control Devices Handbook."
Performing Organization: Daniel Consultants, Inc., Columbia, MD 21405
Expected Completion Date: December 1986
Estimated Cost: $121,400 (FHWA Administrative Contract)

FCP Category 2—Traffic Control and Management

FCP Project 2Q: Urban Network Control

Title: Enhancements to Passer II-84. (FCP No. 42Q1425)
Objective: Improve the treatment of permissive left turns by modifying the current delay model in Passer II-84.
Performing Organization: Texas Transportation Institute, College Station, TX 77840
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1987
Estimated Cost: $80,000 (HP&R)

FCP Category 4—Pavement Design, Construction, and Management

FCP Project 4A: Pavement Management Strategies

Title: Pavement Design Using Rapid Methods of Collecting and Analyzing Deflection Data—Design Procedure Development. (FCP No. 44A3102)
Objective: Develop a rational pavement design procedure for highways and general aviation airfields. Use the procedure in the design of new pavement sections where material properties can, to some extent, be controlled and in the design of overlays for existing pavements.
Performing Organization: Tennessee Department of Transportation, Nashville, TN 37219
Expected Completion Date: March 1987
Estimated Cost: $113,660 (HP&R)

FCP Project 4B: Design and Rehabilitation of Rigid Pavements

Title: Assessment of Load Transfer Across Joints and Cracks in Rigid Pavements Using the Falling Weight Deflectometer (FWD). (FCP No. 44B2324)
Objective: Field test procedures previously developed for evaluating transverse joint efficiency using an FWD and modify, if necessary, to evaluate transverse cracks. Develop a method for using the FWD to evaluate cracks in rigid pavements for load, shear, and moment transfer and to evaluate longitudinal joints, particularly between the mainline and a tied concrete shoulder.
Performing Organization: University of Texas at Austin, Austin, TX 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1990
Estimated Cost: $280,500 (HP&R)

FCP Project 4C: Design and Rehabilitation of Flexible Pavements

Title: Potential Benefits of Geosynthetics in Flexible Pavement Systems. (FCP No. 54C1213)
Objective: Evaluate the potential structural and economic advantages of geosynthetic reinforcement within a granular base and develop practical design guidelines.
Performing Organization: Georgia Institute of Technology, Atlanta, GA 30332
Expected Completion Date: December 1987
Estimated Cost: $50,000 (NCHRP)

Title: Increase of Recycled Asphalt Production Through Use of Styrene-Butadiene Rubber (SBR) Latex. (FCP No. 44C3174)
Objective: Determine whether the use of SBR latex in combination with virgin asphalt and aggregate can be added to recycled materials to improve pavement performance.
Performing Organization: University of Akron, Akron, OH 44325
Funding Agency: Ohio Department of Transportation
Expected Completion Date: March 1987
Estimated Cost: $43,000 (HP&R)

Title: Correction of Wheelpath Rutting. (FCP No. 44C6314)
Objective: Evaluate a proprietary slurry seal type material called "Ralumac" (a blend of latex-modified emulsion, aggregate, type 1 portland cement, water, and additive) used to correct wheelpath rutting in asphalt pavements.
Performing Organization: New Jersey Department of Transportation, Trenton, NJ 08625
Expected Completion Date: July 1989
Estimated Cost: $56,710 (HP&R)

FCP Project 4E: Construction Control and Management

Title: Integration of New Portland Cement Concrete (PCC) Smoothness Monitoring Equipment Into Current Procedures and Specifications. (FCP No. 34E1183)
Objective: Develop data and correlations between outputs from a new device that automatically measures, displays, and records the smoothness of newly placed pavement and those from the current devices. Develop standard procedures and other supporting information that will make the new device easy to use and readily accepted by both contractors and State highway agencies.
Performing Organization: Analysis Group, Inc., Washington, DC 20003
Expected Completion Date: March 1987
Estimated Cost: $74,740 (FHWA Administrative Contract)

FCP Category 5—Structural Design and Hydraulics

FCP Project 5A: Bridge Loading and Design Criteria

Title: Fatigue of Cables in Cable-Stayed Bridges. (FCP No. 55A2012)
Objective: Develop criteria and guidelines for fatigue design of cable stays, and develop practical guidelines for material requirements and for testing wires, strands, and cable stays.
Performing Organization: Freeman Fox Ltd., London, UK
Expected Completion Date: June 1987
Estimated Cost: $125,000 (NCHRP)

Title: Fatigue Strength of Post-tensioned Concrete. (FCP No. 45A2202)
Objective: Examine the fatigue resistance of typical posttensioned concrete girders to determine the effective level of tension stress in the precompressed tensile zone on the capability of posttension girders to withstand traffic loading without fatigue during their design service life. Consider kind of duct, effect of tendon coating, and effect of grouting materials on the fatigue strength of both tendon assemblies and girder.
Performing Organization: University of Texas at Austin, Austin, TX 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1988
Estimated Cost: $100,000 (HP&R)

Title: Guidelines for Multiple-Span Highway Bridges Without Joints. (FCP No. 35A3182)
Objective: Review current design and construction practices and field problems that have developed in long, multiple-span bridges without expansion joints. Compile a state-of-the-art report on this subject and develop comprehensive guidelines for designing such bridges. Address such topics as length and number of spans, kinds and flexibility of piers, kinds of foundations and bearings, and other appropriate design features.
Performing Organization: University of Maryland, College Park, MD 20742
Expected Completion Date: March 1987
Estimated Cost: $94,890 (FHWA Administrative Contract)

Title: Augmentation of Shortcut Design Techniques for Concrete Box Girders. (FCP No. 45A4082)
Objective: Provide a complete software package for use in the design of concrete box girder bridges with monolithic slabs.
Perfoming Organization: California Department of Transportation, Sacramento, CA 95807
Expected Completion Date: September 1987
Estimated Cost: $40,000 (HP&R)

☆ U.S. Government Printing Office: 1986—491-825/40003

FCP Project 5H: Highway Drainage and Flood Protection

Title: Microcomputer Software for Storm Drain Hydraulic Grade Line Computations. (FCP No. 45H3722)
Objective: Develop and code hydraulic grade line procedures for the storm drain program that will be incorporated into the integrated drainage design computer system.
Performing Organization: University of Virginia, Charlottesville, VA 22903
Funding Agency: Virginia Department of Highways and Transportation
Expected Completion Date: June 1987
Estimated Cost: $33,500 (HP&R)

Title: Overtopping Damage Minimization. (FCP No. 35H4062)
Objective: Evaluate the performance of various roadway surface and embankment treatments, and conduct scale model tests of a select group of the most promising treatments to determine the most effective, esthetic, maintenance-free, and inexpensive systems for stabilizing embankments during overtopping.
Performing Organization: Simons, Li, and Associates, Inc., Fort Collins, CO 80522
Expected Completion Date: May 1988
Estimated Cost: $90,000 (FHWA Administrative Contract)

FCP Project 5K: Bridge Rehabilitation Technology

Title: Guidelines for Evaluating Corrosion Effects in Existing Steel Bridges. (FCP No. 55K2122)
Objective: Develop practical guidelines to assess the effects of corrosion on structural details in steel highway bridges. Ensure that the guidelines apply to all of the steps involved in evaluating the effects of corrosion on the performance of existing bridges and that they are suitable for incorporation into AASHTO's "Manual for Maintenance Inspection of Bridges."
Performing Organization: Modjeski and Masters, Inc., Harrisburg, PA 17105
Expected Completion Date: September 1988
Estimated Cost: $300,000 (NCHRP)

Title: Strategies for Bridge Replacement. (FCP No. 45K4062)
Objective: Develop a practical methodology for prioritizing bridge structure rehabilitation and replacement for both onsystem and offsystem bridges in Texas.
Performing Organization: Center for Transport Research, Austin, TX 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1988
Estimated Cost: $80,000 (HP&R)

FCP Project 5Z: Implementation of Structural and Hydraulics R&D

Title: Microcomputer Programs for Hydraulic Design of Drainage Structures. (FCP No. 35ZH088)
Objective: Develop microcomputer programs for various hydraulic design procedures, and write a users manual detailing the program and its proper use. Develop programs for the following design areas: Bridge waterways, culvert outlet protection, open channels, pumping stations, local scour, storm drainage systems, reservoir routing, and structural culvert design.
Performing Organization: University of Colorado at Denver, Denver, CO 82020
Expected Completion Date: December 1986
Estimated Cost: $49,945 (FHWA Administrative Contract)

FCP Category 0—Other New Studies

Title: Concrete Coating Problems. (FCP No. 40M3972)
Objective: Evaluate the problems with concrete coatings, including reported cases of flaking, peeling, and darkening. Conduct a laboratory and field exposure program to investigate conformance of materials to Texas' specifications and performance of various coatings and surface preparation variables.
Performing Organization: University of Texas at Austin, Austin, TX 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1986
Estimated Cost: $50,000 (HP&R)

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Elizabeth Hanford Dole, *Secretary*

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U.S. Department of Transportation
Federal Highway Administration
Washington, DC 20590

COVER: In an FHWA study, the effects of reduced lighting techniques on traffic operations and safety were addressed as well as the costs, potential energy savings, and legal implications of these techniques.

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The Secretary of Transportation has determined that the publication of this periodical is necessary in the transaction of the public business required by law of this Department.

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The Potential for Reduced Lighting on Roadways

by

Michael S. Janoff, Loren K. Staplin, and John B. Arens

To put the recommendations resulting from the research described in this article into proper context, the reader must be aware that although target detection may deteriorate only slightly under some of the reduced lighting conditions used in this study, the standards guiding practically all lighting designs of public roads in the United States reflect at least the minimum criteria set forth in the American National Standard Practice for Roadway Lighting (ANSI/IES RP-8, 1983). This document has been developed and is kept current by the members of the Roadway Lighting Committee of the Illuminating Engineering Society of North America and represents the national consensus of all groups having an essential interest in the provisions of this standard. The criteria, which set the minimum lighting levels considered safe for nighttime visibility and traffic conditions, are the result of ongoing work by representatives of the engineering community, various governmental bodies, academia, manufacturers, consultants, utility companies, and user groups. It is the authors' strong opinion and recommendation that, regardless of the findings demonstrated for the particular research context addressed in this study, lighting should not be reduced below ANSI minimum levels unless and until such ANSI standards may be changed.

Introduction

Over 50 percent of all motor vehicle fatalities occur in darkness even though only 25 percent of all motor vehicle travel occurs at night. (*1*)[1] This overrepresentation has been used as a justification for installing fixed lighting on many roadways. However, research to determine how such fixed lighting affects the frequency and severity of nighttime accidents appears to be mixed because accident frequencies and severities also depend on a host of geometric and traffic factors including traffic density and how it relates to the roadway's capacity, and the complexity of the driver's visual search task.[2]

[1] Italic numbers in parentheses identify references on page 42.

[2] "Road Lighting as an Accident Countermeasure," Technical Report No. 8/2, 4th draft, International Commission on Illumination, Paris, France, November 1982.

Over the past decade during periods of energy shortages, several highway agencies extinguished roadway lighting to reduce maintenance and operating costs. However, lighting frequently was restored when nighttime accidents increased or citizens pressured the agencies. (*2–4*) One fundamental problem with this reduced lighting technique was that lighting was reduced or eliminated for the entire nighttime period rather than only when traffic density was low.

Because of budget constraints, highway and lighting agencies continue to be interested in energy conservation. With the availability of modern, solid-state dimming circuitry for high intensity discharge (HID) lamps, it is possible to provide full lighting when traffic density is high and the roadway operates near capacity and to reduce lighting as the traffic density decreases. Considerable energy thus can be saved while still providing the benefits of full lighting at locations and times when driver decisionmaking is the most critical and visibility needs are the greatest.

Before such reduced lighting techniques can be implemented, however, their effects on traffic operations and safety must be quantified, their costs and energy-reduction benefits determined, and any legal implications investigated.

This article summarizes the results of a Federal Highway Administration (FHWA) study to determine if roadway lighting can be reduced or eliminated during nighttime periods when traffic density is much lower than design capacity without significantly reducing drivers' abilities to safely and effectively control their vehicles. (*5*) The study consisted of several tasks, including the following:

- A review of the literature and State and foreign experiences.
- The development of a conceptual model of visibility needs and the identification of alternative reduced lighting techniques—including no lighting, every other luminaire extinguished, luminaires on one side of a roadway extinguished, and different kinds and levels of dimming.
- The determination of the costs, potential energy savings, and legal implications of these reduced lighting techniques.
- The determination of the effect of such techniques on driver detection of simulated roadway hazards under actual traffic conditions.

The study concluded the following:

- Present technology exists for implementing all of the identified reduced lighting techniques, with benefit-cost ratios (where benefits are the savings resulting from lower energy consumption and costs are the costs of implementing the various techniques) greater than 1.0 for all but the most complex techniques.
- Driver detection performance decreased under each reduced lighting technique—minimally so for dimmed and every other extinguished and significantly so for one side extinguished and no lighting.
- Legal problems may result with the use of reduced lighting techniques.

Study recommendations include using dimming circuits, primarily for new systems, with extinguishing every other luminaire for either new or existing systems an inexpensive alternative, provided applicable lighting standards for the quality and quantity of the lighting still are met.

Selecting Reduced Lighting Techniques

A broad range of reduced lighting techniques was identified from a literature review and information obtained from worldwide lighting agencies (table 1). Various techniques were identified including extinguishing all or some of the luminaires after a designated time, installing two luminaires on each pole and extinguishing one after a designated time, and using dimming circuits to reduce the lighting by a uniform or variable amount after a designated time or as a function of traffic volume or driver visibility.

Based on preliminary analyses of costs, benefits, and availability, the following six lighting conditions were selected for evaluation:

- Full lighting.
- Dimming to 30-percent light output.[3]
- Dimming to 50-percent light output.[3,4]
- Extinguishing every other luminaire.
- Extinguishing luminaires on one side of the roadway where luminaires are located on both sides of the roadway.
- No lighting.

Effects of Reduced Lighting on Traffic Operations and Safety

Three experiments were designed and conducted to determine the effect of the six lighting conditions on traffic operations and safety. These included a pilot experiment to evaluate the extreme lighting conditions (full lighting, no lighting) on driver performance at extreme geometric (straight and level, interchange ramp) locations; a controlled field experiment to evaluate the effect of the lighting conditions at a single (mainline) geometry; and an observational validation experiment to observe the reactions of naive, unalerted motorists under three selected lighting conditions.

Pilot experiment

The experimental design, data collection, and data analysis were accomplished in the same manner as in the controlled field experiment (described in the next section). The primary result of the pilot experiment was that there was a significant decrease in driver performance when lighting was extinguished on interchange ramps but little reduction in performance when lighting was extinguished on mainline sections. Thus, the pilot experiment demonstrated that lighting should not be extinguished on interchange ramps, but the potential exists for extinguishing lighting on mainline sections. (*5*)

[3] Either uniform or variable dimming.

[4] Either dim or extinguish one of two lamps.

Table 1.—Reduced lighting techniques

Technique	Freeway/ nonfreeway	Where implemented
Every other light extinguished 1 a.m. to 4 a.m.	Freeway	Chicago, IL
Every other light extinguished after midnight or 1 a.m.	Nonfreeway	Los Angeles, CA
All lighting extinguished	Freeway	Virginia; Milwaukee, WI
One side extinguished	Freeway	Texas
Every other light extinguished	Nonfreeway	Clearwater, FL
Two-lamp luminaire—one extinguished after midnight	Freeway	Oshawa, Ontario
Time-dependent variable level (two levels)	Nonfreeway (first system) Freeway (second system)	Philadelphia, PA
Time- and volume-dependent variable level system	Freeway	Highway 401, Ontario, Canada
Time-, volume-, visibility-, and weather-dependent variable level system	Freeway	Zurich, Switzerland

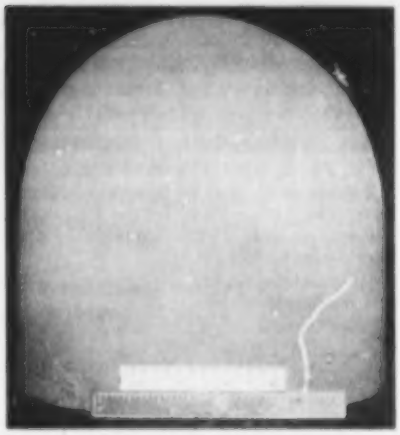


Figure 1.—Three-dimensional target.

Controlled field experiment

Data were collected in both the pilot and controlled field experiments on a 6-mi (9.7-km) portion of I-95 in the Philadelphia and Bucks County, Pennsylvania, area. This multilane, urban/suburban roadway is fully lit in Philadelphia and unlit in Bucks County. The lighting system consists of 200-W high-pressure sodium (HPS) lamps mounted 30 ft (9.1 m) at spacings of between 68 and 88 ft (20.7 and 26.8 m) in a staggered arrangement. Table 2 summarizes the photometric measurements (*6*) associated with the six different lighting conditions evaluated in this experiment.

The principal dependent measure selected for both the pilot and controlled field experiments was the distance at which drivers first could detect a simulated hazard—the target—in the roadway ahead of their vehicles.[5] It was hypothesized that as the lighting was reduced, the distance at which the driver detected the simulated hazard would decrease, and this change would serve as a surrogate measure of the relative changes in safety with the various reduced lighting techniques.

Additional dependent measures included brief subjective ratings of target visibility and responses to a questionnaire.

The target selected as a simulated hazard was a 6-in (0.15-m) styrofoam hemisphere with a 6-in (0.15-m) diameter skirt (fig. 1), used by the researchers in previous visibility and lighting studies. (*8*) This size was selected to agree with the size of the object used in the AASHTO computation of safe stopping distance. (*6*) When evaluating four of the lighting conditions, the target, painted a flat, 18-percent reflectant gray, was placed in the roadway shoulder lane at the points of maximum and minimum horizontal illuminance. When evaluating the no lighting and the one side extinguished conditions, only one target position was used because there was negligible longitudinal variability in horizontal illuminance.

The lighting on the every other extinguished, one side extinguished, no lighting, and full lighting test sections was uniform during the entire data collection period. The full and no lighting conditions did not require the lighting circuit to be changed; fuses were removed from the appropriate electrical circuits for the other two conditions.

The two dimmed conditions were obtained on the same section of roadway by installing a dimming circuit and setting the luminaire power to either 75 or 50 percent (50- or 30-percent light output, respectively).

Twenty-four subjects were tested under each of the six lighting conditions. As a control, starting points and order of presentation were distributed evenly across the six conditions. Further, for those lighting conditions that included two target positions, at random, half of the test subjects responded to the target under maximum horizontal illuminance and the other half responded to the target under minimum horizontal illuminance.

[5] This same measure has been used successfully in past lighting and visibility research to quantify the effect of visibility on a similar form of driver performance. (*7*)

Table 2.—Summary of photometric measurements

Photometric measure	Lighting condition: Full lighting	75-percent power[1]	50-percent power[2]	Every other extinguished	One side extinguished	No lighting
Horizontal illuminance—$E_{h_{ave}}$(fc)	1.15	0.58	0.35	0.58	0.04	0.01
Uniformity—($E_{h_{ave}}/E_{h_{min}}$)	4.50	4.14	4.19	14.50	—	—
Average pavement luminance—L_b(fL)	0.58	0.29	0.15	0.27	0.049	0.016
Object luminance—L_t(fL); 18-percent reflectant gray	0.23	0.17	0.12	0.18	0.10	0.03
Veiling luminance—L_v(fL)	0.39	0.19	0.07	0.25	0.14	0.01
Contrast—$(L_t - L_b)/L_b$	−0.60	−0.41	−0.20	−0.33	1.04	0.88
Visibility Index—$VI = CxRCS_{L_b}DGF$[3]	8.78	4.43	1.66	2.93	2.82	1.57

[1] Approximately 50-percent light, relative to full lighting condition.

[2] Approximately 30-percent light, relative to full lighting condition.

[3] C = contrast; RCS = relative contrast sensitivity; DGF = disability glare factor = $\frac{L_b \times RCS_{L_b'}}{L_{b'} \times RCS_{L_b}}$, where $L_{b'} = \frac{L_b + L_v}{1.074}$.

Visual acuity data for each subject was obtained in a separate laboratory session using a standard Snellen chart. In addition, a contrast sensitivity screening technique was performed. Each visual performance measure was collected under two ambient light levels (target luminance)—0.4 fL (1.4 cd/m²) and 4.0 fL (13.7 cd/m²) (luminance level of plain white chart background).

Subjects were tested individually in the 1½-hour experiment which included the following:

- A simple reaction time test—a pushbutton response to a high-contrast visual stimulus (a red light emitting diode [LED] viewed against a black surround) to eliminate the effect of individual reaction time from the observed response magnitude.
- The six road trials.
- Subjective ratings of target visibility.
- A brief questionnaire on target realism and perceived safety effects of reduced lighting that was completed after the road trials were conducted.

In the road trials, the experimenter rode with the subject, and assistants were stationed out of view, slightly off the roadway shoulder. The vehicle was instrumented with a counting device linked directly to the transmission to measure the distance traveled from a designated reference point. A response button wired into the counting device was mounted in the center of the steering wheel.

During each trial, the experimenter directed the subject to pull onto the shoulder of the roadway at a reference point located at least ¼ mi (0.4 km) before the target. The experimenter then radioed the assistant to place the target in the shoulder lane. The test vehicle then re-entered the traffic stream, and the counting device was engaged. Subjects were required to drive at the 55-mi/h (89-km/h) speed limit.

When the subject first detected the target, he/she pushed the response button, which "froze" the counting device, indicating the distance traveled since the reference (radio contact) point. This display reading then was subtracted from the premeasured distance from the reference point to the target to yield the distance to the target at which the response button was pushed.

After each detection response, subjects were asked to rate target visibility on a 10-point bipolar scale.

When the six road trials were completed, each subject rated the target's realism as a roadway hazard and the perceived safety effects of implementing reduced lighting techniques.

Results of controlled field experiment

The results in table 3 show that the best (mean) detection performance was achieved under the full lighting condition, with orderly decrements in performance noted for the uniform dimming to 75-percent power, uniform dimming to 50-percent power, and every other luminaire extinguished conditions, respectively. The one side extinguished and the no lighting conditions had the poorest performance levels. The repeated measures analysis of variance of these data demonstrated highly significant main effects, even with a considerable amount of variability in subjects' performance. Further, the apparent linear pattern in the detection data was confirmed through a trend analysis.

Statistical tests demonstrated significant differences at the 0.05 level between full lighting and one side extinguished and no lighting and between full lighting and the other five conditions.

The subjective ratings of target visibility, also presented in table 3, resulted in markedly higher mean ratings for full lighting; a cluster of moderate ratings for the uniformly dimmed, every other extinguished, and no lighting conditions; and a somewhat isolated lower rating for the one side extinguished lighting condition. Also, the subjects' measured visual acuity/contrast sensitivity correlated poorly with the target detection performance.

Next, the linear regression was computed between the detection performance data and several lighting/visibility indices. The resulting coefficients are: With average horizontal illuminance, $r = 0.95$; with average pavement luminance, $r = 0.94$; and with Visibility Index values (VI)[4], $r = 0.83$ (figs. 2–4).

[4] See table 2.

Table 3.—Results of controlled field experiment

Lighting condition	Behavioral data: Detection distance to target		Subjective data: Target visibility[1]	
	Mean	Standard deviation	Mean	Standard deviation
	Feet	*Feet*		
Full lighting	287.9	190.3	7.9	2.1
75-percent power	232.6	124.8	7.1	2.1
50-percent power	223.8	97.0	7.3	2.1
Every other extinguished	204.8	92.5	6.8	2.3
One side extinguished	163.4	73.8	6.3	2.7
No lighting	163.2	44.1	7.0	2.8

[1] In rating target visibility, 1 = very poor; 10 = very good.
1 ft = 0.305 m

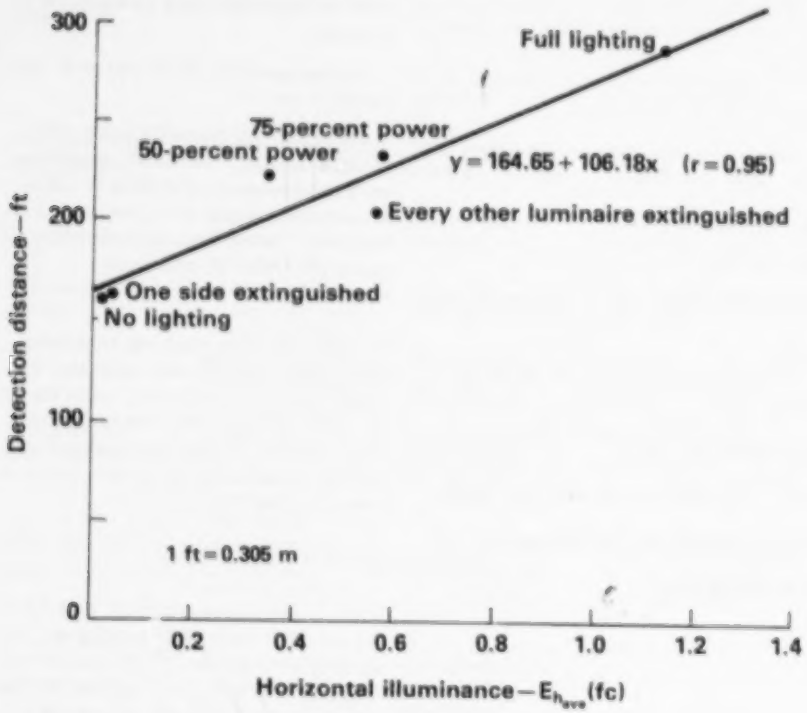


Figure 2.—Average horizontal illuminance versus detection distance.

Subjective responses to target realism and perceived safety effects of reduced lighting indicated that drivers felt that the target simulated a hazard reasonably well, felt very negative toward reducing lighting on ramps or interchanges, and felt slightly negative to ambivalent toward reducing lighting on straight, mainline roadway sections.

Observational validation experiment

An observational validation experiment using the same roadway and target as in the pilot and controlled experiments was conducted to document differences in gross driver/vehicle responses (for example, swerves/lane changes, brake actuation, and high-beam use) as a function of full lighting, uniformly dimmed lighting to 50-percent power, and no lighting. These responses were taken as indicators of a perceived hazard on the roadway. It was expected that the trend in observational data would parallel the controlled experiment data for the same lighting conditions.

Results of observational validation experiment

The results of this experiment are shown in table 4. Lateral shifts and braking reactions are included in the response totals—no high-beam use occurred.

The response percentages demonstrate a pattern corresponding to the detection measure under the same lighting conditions in the controlled field experiment. Also, the nearly identical mean vehicle velocities noted for the respective conditions indicate that the ambient lighting condition itself affected target visibility.

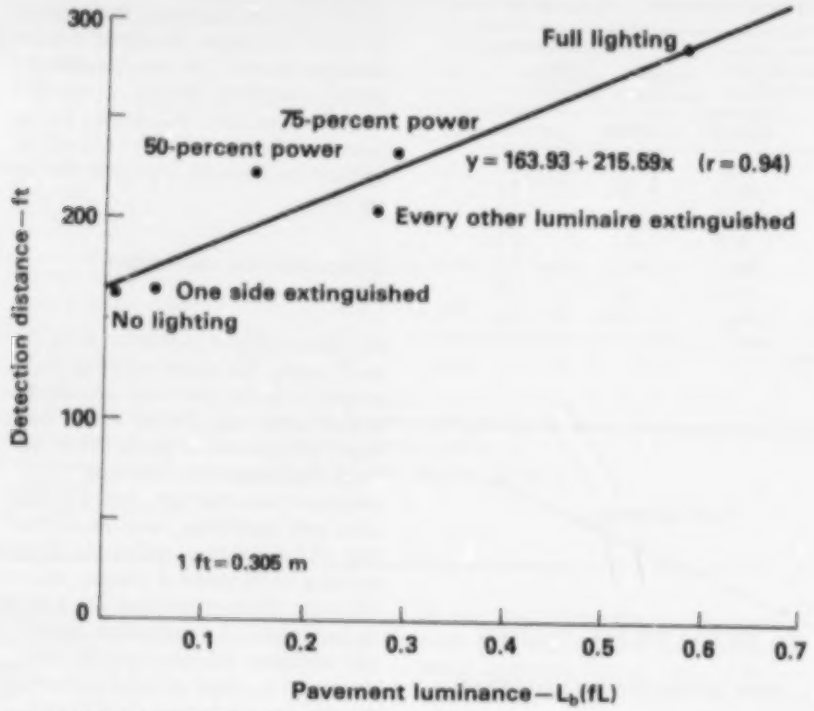


Figure 3.—Average pavement luminance versus detection distance.

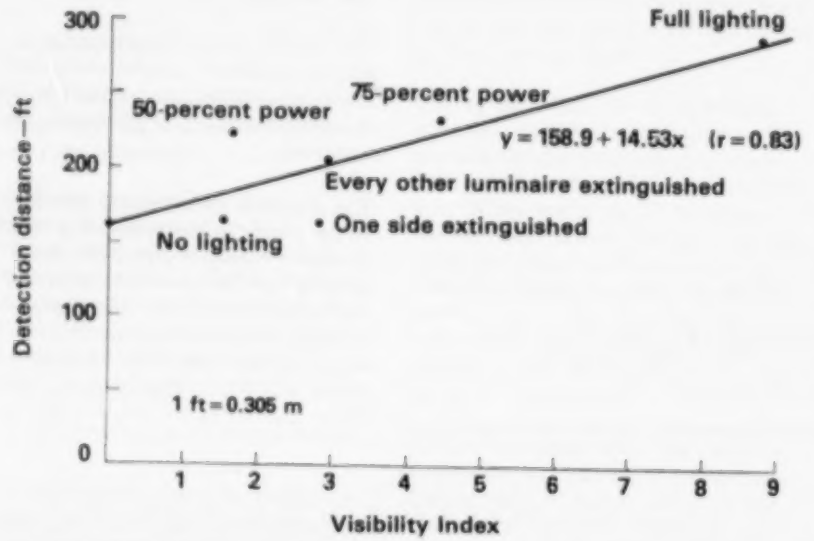


Figure 4.—Visibility Index versus detection distance.

Economic Analysis

An economic analysis of alternative reduced lighting techniques was performed to compute the costs, energy savings, and benefit-cost ratios for each technique.

The following assumptions and simplifications were made for these analyses:

- Only group-controlled lighting circuits were used for all costs.
- A cost of 6.4 cents per kWh was used.[7]
- Only one lamp (200-W HPS) was used for all systems except the two-lamp luminaire in which two 100-W HPS lamps were used to equalize wattage.
- A discount rate of 10 percent was used.
- All costs and benefits were computed on a per mile basis, assuming an average spacing of 92.5 ft (28.2 m) between lights for a two-sided system.[8] This yields approximately 57 poles per mile (35 poles per kilometer).
- Costs of items such as luminaires, timeclocks, photocells, cabinets, contactors, wiring, and labor were based on 1984 Philadelphia, Pennsylvania, costs; costs of specialized dimming circuitry were obtained from the manufacturers or users.

Costs of techniques

Table 5 lists the equipment and labor required for each of the reduced lighting techniques. For some of these techniques, two approaches are described (for example, photocell/timer or timeclock). Based on the assumptions described previously and the equipment and labor required, the costs for each of the reduced lighting techniques were developed (table 6).

[7] The figure of 6.4 cents per kWh was derived from Edison Electric Institute data and is a nationwide average for street lighting electric costs. Although this average was used in all energy cost calculations, the actual street lighting electric costs found in the United States range from about 1.5 cents to 12 cents per kWh.

[8] Derived from a brief survey of typical freeway systems in the Delaware Valley.

Table 4.—Results of observational validation experiment

Lighting condition	Sample size	Total responses[1]	Mean vehicle approach velocity
		Number (percent)	*Miles per hour*
Full lighting	72	13 (18)	58
Uniformly dimmed—50-percent power	69	9 (13)	59
No lighting	71	5 (7)	56

[1] Braking and/or lane changing.

1 mi/h = 1.6 km/h

Table 5.—Equipment and labor requirements

Technique	Requirement		
	Equipment	Labor	Comments
All off after midnight	(a) Photocell/timer	Replace photocell with photocell/timer	ARL watt-4 photocell; automatic reset after power failure
	(b) Timeclock, cabinet, and wiring	Install equipment (minimal)	Must be manually reset after power failure
Every other off after midnight	(a) Photocell/timer, contactor, cabinet, and wiring	Split circuit, add photocell/timer, etc.	ARL watt-4 photocell; unequal burn time
	(b) Timeclock, contactor, cabinet, and wiring	Split circuit, add timeclock, etc.	Must be manually reset after power failure
One side off after midnight	(a) Photocell/timer, contactor, cabinet, and wiring	Split circuit, add photocell/timer, etc.	ARL watt-4; unequal burn time
	(b) Timeclock, contactor, cabinet, and wiring	Split circuit, add timeclock, etc.	Must be manually reset after power failure
Two-lamp luminaire—one off after midnight	Two-headed luminaire, timer, and circuitry (Oshawa, Ontario system)	Replace luminaires plus additional wiring	Circuits to alternate luminaires
Preset light reduction	Photocell/timer, control box (Lutron), cabinet, and wiring	Replace photocell and add box, cabinet, and wiring	Timeclock also can be used as alternative to photocell/timer
Volume- and time-dependent variable light reduction	Special ballasts, dimming circuits, computer control, wiring, etc. (A. Ketvirtis, Ontario system)	Replace ballasts and add computer and volume sensing equipment	Wide Lite ballast

The costs for the all extinguished, one side extinguished, and every other luminaire extinguished techniques apply to both new and retrofitted lighting systems—all three require simple switching and timing equipment to be installed in the group-controlled circuits.

The costs for the two-lamp luminaire, uniform dimming, and variable dimming techniques apply only to new lighting systems. Costs for retrofitting probably would be 20 percent more for dimming (relatively easy to retrofit) but much higher for the two-lamp luminaire system, which would have to be modified substantially.

Potential energy savings of techniques

Based on an annual full nighttime operation of 4,200 hours (*9*) (half night = 2,100 hours) and an energy cost of 6.4 cents per kWh, the potential energy savings for each of the techniques were derived and are presented in the first column of table 7.

Benefit-cost ratios of techniques

Combining the data in table 6 with that in the first column of table 7, benefit-cost ratios were derived for each of the reduced lighting techniques, as shown in table 7. When alternative approaches were available (for example, photocell/timer or timeclock), the least expensive was used. When two or more costs were derived for a given technique (two different variable dimming methods), the average cost was used. Ranges also are noted for the averaged cases.

The most complex dimming system (variable dimming) will not prove to be cost-effective (benefit-cost ratio of at least 1.0 is cost-effective); the simpler systems will have very high benefit-cost ratios (benefit-cost ratio = 20.0).

Table 6.—Costs of reduced lighting techniques

Technique	Initial costs: Equipment	Initial costs: Labor	Initial costs: Per pole	Initial costs: Per mile	Annual costs per mile (10% discount)
	Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*
All off after midnight	(a)[1] 62.00	38.00	2.00	114.00	11.00[2]
	(b) 450.00	450.00	18.00	1,026.00	103.00
Every other off after midnight	(a) 300.00	300.00	12.00	684.00	68.00[3]
	(b) 450.00	450.00	36.00	1,026.00	103.00
One side off after midnight	(a) 300.00	300.00	12.00	684.00	68.00[3]
	(b) 450.00	450.00	36.00	1,026.00	103.00
Two-lamp luminaire—one off after midnight (new system)	–	–	–	7,650.00	765.00
Preset light reduction:					
Lutron Regulator ballast	3,000.00 per 54 lamps	1,500.00 per 54 lamps	83.00	4,731.00	473.00
Lutron Reactor ballast	3,000.00 per 30 lamps	4,000.00 per 30 lamps (disconnect capacitor from each lamp)	233.00	13,281.00	1,328.00
Volume- and time-dependent variable light reduction:					
New system in Canada	–	–	400.00	22,600.00	2,260.00
Wide Lite (retrofitted) system	500.00 per ballast plus 2,150.00 control	13,575.00	815.00	46,455.00	4,646.00

[1] (a) refers to photocell/timer and (b) refers to timeclock/contactor.

[2] For individual control, the costs are $570.00 and $296.00, respectively.

[3] For individual control, the costs are $285.00 and $182.00, respectively.

1 mi = 1.6 km

This analysis does not include the possibility of maintenance costs or energy costs increasing or the effects of reduced lighting on traffic operations and safety. In addition, three of the costs are based on new systems that have lower costs than those of retrofitted systems. Thus, the benefit-cost ratios in table 7 may be optimistic.

To compare these energy costs with the safety benefits, a sensitivity analysis was performed. On I-94 in Chicago, Illinois, the nighttime lit/unlit accident rate differential varied from 1.6 to 0.27 per million vehicle-miles (1.00 to 0.17 per million vehicle-kilometers). (*10*) The potential safety benefits for 1,000 mi (1 600 km) of lit freeway, assuming only the energy costs, were computed for an accident differential of 0.27 per million vehicle-miles (0.17 per million vehicle-kilometers).

Using the net annual energy savings per mile—$1,820 ($1,131 per kilometer) (energy savings minus cost of implementation)—resulting from extinguishing lighting after midnight, the use of lighting would have to prevent 0.46 accidents per mile (0.29 accidents per kilometer) assuming an average cost per accident of $4,000. (*11*) For 1,000 mi (1 600 km) of roadway, this equates to 455 accidents. Table 8 shows that for nighttime traffic volumes of more than 4,617 vehicles, the benefit-cost ratio is greater than 1.0. Therefore, it is cost-effective to leave the lights on when the nighttime traffic volume exceeds 4,617 vehicles or 770 vehicles per lane or 128 vehicles per lane per hour, assuming a six-lane roadway and a 6-hour lights-on-or-off consideration.

Legal Analysis

Two approaches were used to determine what legal problems might be incurred by a lighting agency using reduced lighting—a review and critique of the legal literature and a compilation and analysis of legal opinions of experts on how the laws should be interpreted.

Literature review

A review of the existing literature revealed that under both the common law and State Tort Claims Acts, the threat of liability exists for a public entity that seeks to reduce or eliminate lighting during periods of low traffic density. Any agency planning such a program should be advised that extensive scientific research and study are required. Even then, of course, a lawsuit may not be avoided, but at least the probability of a plaintiff's recovery is lessened.

Table 7.—Benefit-cost ratios of reduced lighting techniques

Technique	Annual energy savings per mile	Annual costs per mile	Average benefit-cost ratios	Range of benefit-cost ratios
	Dollars	*Dollars*		
All off after midnight	1,877.00	11.00–103.00	100	18–171
Half off (every other off or one side off) after midnight	938.00	68.00–103.00	12	9–14
Two-lamp luminaire—one off after midnight	938.00	765.00	1.2	1.2
Preset light reduction—uniform dimming (50-percent power)	938.00	473.00–1,328.00	1.0	0.7–2.0
Volume- and time-dependent variable light reduction—variable dimming (50-percent power)	938.00	2,260.00–4,646.00	0.3	0.2–0.4

1 mi = 1.6 km

Table 8.—Safety benefit-cost ratios associated with lighting 1,000 miles of roadway

Nighttime traffic volume	Expected number of accidents reduced	Benefit-cost ratios
1,000	99	0.2
2,000	197	0.4
4,000	394	0.9
4,617	455	1.0
5,000	493	1.1
10,000	986	2.2

1 mi = 1.6 km

Legal opinions

Legal opinions were obtained by contacting on the telephone and sending questionnaires to lighting engineers, consultants, and attorneys, who either worked for municipal or State agencies or were in private practice. The opinions were classified as follows:

Opinion	Percent of responses
Wait for more research	28
Definite problem	22
Defense exists	28
Liability questionable	22

Whether the respondent was a State/municipal employee or a private employee or whether the respondent was an attorney did not significantly affect the distribution of opinions.

The diversity of the responses summarized above reinforces the conclusion that tort liability will be an issue if lighting is reduced—especially below ANSI/IES recommended values.

Recommendations

Based on the results of this research, the following recommendations have been developed on the proposed use of reduced roadway lighting during periods of low traffic density:

- Uniform dimming circuits effectively reduce the energy required for roadway lighting while only resulting in a minimal, nonstatistically significant adverse effect on driver performance. Energy savings of up to 25 percent[a] can be achieved, and at an average nationwide energy cost of 6.4 cents per kWh, the benefit-cost ratio is about 1.0. For higher energy costs, the benefit-cost ratio would exceed 1.0.

The initial installation costs for such systems are, however, relatively high, and higher for existing lighting systems than for new installations.

- In urban or suburban centers where lighting levels far exceed ANSI/IES minimum requirements because of the commercial nature of the area, an inexpensive technique for conserving energy would be every other luminaire extinguished. Benefit-cost ratios for this technique range between 9 and 14 for average nationwide energy costs. Because most roadway lighting installations are designed so that extinguishing every other luminaire would result in uniformity ratios and lighting levels considerably below those suggested by AASHTO (*12*) and endorsed by FHWA, it is impossible to issue an unqualified recommendation to implement this energy conservation technique. Agencies contemplating such a step first should assure that the lighting is still in conformance with established AASHTO guidelines.

[a] Fifty percent during half of the night.

• The variable dimming circuits are not recommended because of high costs resulting in low benefit-cost ratios, and the one side extinguished technique is not recommended because of its highly significant adverse impact on driver performance. The research shows that an agency would be better off extinguishing *all* lights on a roadway rather than on one side only.

• Using two-lamp luminaires in newly designed lighting systems (where one lamp can be extinguished) can save up to 25 percent of the energy. The effect of this reduced lighting technique on driver performance is minimal (that is, the same as a dimmed circuit); however, this technique probably would be too expensive to implement in existing lighting systems.

• Reduced lighting techniques should not be implemented before 11 p.m. in most urban areas because traffic density remains relatively high until that time. Regularly scheduled sports events and other large traffic generators could change this time to still a later hour. Cities with little or no evening activity might reduce lighting earlier than 11 p.m.

To apply the preceding recommendations, an agency must be aware of the potential legal problems and ensure that lighting is still in conformance with established AASHTO guidelines and ANSI/IES minimum requirements and modify the energy side of the benefit-cost ratio computation to reflect local energy costs.

REFERENCES

(1) "Accident Facts," *Statistics Department, National Safety Council,* Chicago, IL, 1983.

(2) S.H. Young, "Turn on the Lights!" *Lighting Design and Application,* June 1982, pp. 28-32.

(3) S.H. Richards, "Effects of Turning Off Selected Roadway Lighting as an Energy Conservation Measure," Transportation Research Record No. 611, *Transportation Research Board,* Washington, DC, 1981.

(4) M.H. Hilton, "Continuous Freeway Illumination and Accidents on a Section of I-95," *Virginia Highway and Transportation Research Council,* Charlottesville, VA, August 1978.

(5) L.K. Staplin, M.S. Janoff, and L.E. Decina, "Reduced Lighting on Freeways During Periods of Low Traffic Density," Report No. FHWA/RD-86/018, *Federal Highway Administration,* Washington, DC, August 1986.

(6) Illuminating Engineering Society of North America, "American National Standard Practice for Roadway Lighting," ANSI/IES RP-8, 1983.

(7) V.P. Gallagher and P.G. Meguire, "Contrast Requirements of Urban Drivers," Driver Visual Needs in Night Driving, TRB Special Report No. 156, *Transportation Research Board,* Washington, DC, 1975.

(8) M.S. Janoff et al., "Effectiveness of Highway Arterial Lighting," Report No. FHWA-RD-77-37, *Federal Highway Administration,* Washington, DC, July 1977.

(9) P.C. Box, "Relationship Between Illumination and Freeway Accidents," IERL Report, Project 88-67, *Illuminating Engineering,* May/June 1971.

(10) P.C. Box, "Freeway Accidents and Illumination," Highway Research Record 416, *Highway Research Board,* Washington, DC, 1972.

(11) B.C. Kragh, T.R. Miller, and K.A. Reinert, "Accident Costs for Highway Safety Decisionmaking," *Public Roads,* vol. 50, No. 1, June 1986, pp. 15-20.

(12) "An Informational Guide for Roadway Lighting," *The American Association of State Highway and Transportation Officials,* 1984.

Michael S. Janoff is the owner of JMJ Research, a consulting firm specializing in highway transportation research. He has over 20 years of experience in the areas of roadway lighting and visibility, with emphasis on the effects of lighting on traffic safety and performance. Before establishing his own firm, Mr. Janoff was a senior associate at KETRON, Inc., where he managed its Transportation Research Group.

Loren K. Staplin is a senior human factors psychologist in the Transportation Research Group at KETRON, Inc. Dr. Staplin has served as coprincipal investigator on an FHWA study of reduced night lighting on freeways and as principal investigator on a number of traffic research projects for the Pennsylvania Department of Transportation. For 3 years he was a visiting faculty member at Lehigh University in Bethlehem, Pennsylvania, and has worked as a consultant with the Air Force Human Resources Laboratory at Williams Air Force Base in Chandler, Arizona.

John B. Arens is an illumination engineer in the Traffic Safety Research Division, Office of Safety and Traffic Operations Research and Development, FHWA. He was the technical monitor for the study discussed in this article and is involved with research dealing with nighttime visibility and roadway safety. Before joining FHWA, Mr. Arens spent more than 20 years with the Outdoor Lighting Division of Westinghouse Electric in various engineering and marketing positions.

Corrosion in Reinforced Soil Structures

by
Salem D. Ramaswamy and Albert F. DiMillio

Introduction

Soil reinforcement—the inclusion of resistant elements in an engineered soil mass to form a composite material that brings out the best features of both the soil (compressive and shear strength) and the reinforcement (tensile strength)—has emerged as one of the most significant advances in geotechnical engineering (fig. 1). Reinforced soil structures are particularly well suited for retaining walls, bridge abutments, embankments, and cut slopes (fig. 2). *(1)*[1]

A major design aspect of a reinforced soil structure requires tensile loads between the reinforcing elements and the surrounding soil to be transferred by friction and passive soil resistance. The relative contributions of friction and passive resistance depend on soil type and reinforcing elements. For example, strips and sheet reinforcing elements provide mostly frictional resistance, with some passive soil resistance provided by ribs or ridges on the surface of the reinforcement. Grid systems provide frictional resistance from the longitudinal elements and passive resistance from the interconnected transverse elements (fig. 3).

Other major design considerations are the tensile strength and durability of the reinforcing elements. Unanticipated loss of cross-sectional area because of corrosion can result in abrupt and tragic structural failure. Current design methods for reinforced soil structures rely on the calculation of material thicknesses to resist the applied loads plus an additional sacrificial thickness to counteract corrosion losses over the anticipated design life of 75 to 100 years.

This article presents an overview of corrosion problems in reinforced soil structures and describes current research by the Federal Highway Administration (FHWA) to provide solutions.

[1] Italic numbers in parentheses identify references on page 48.

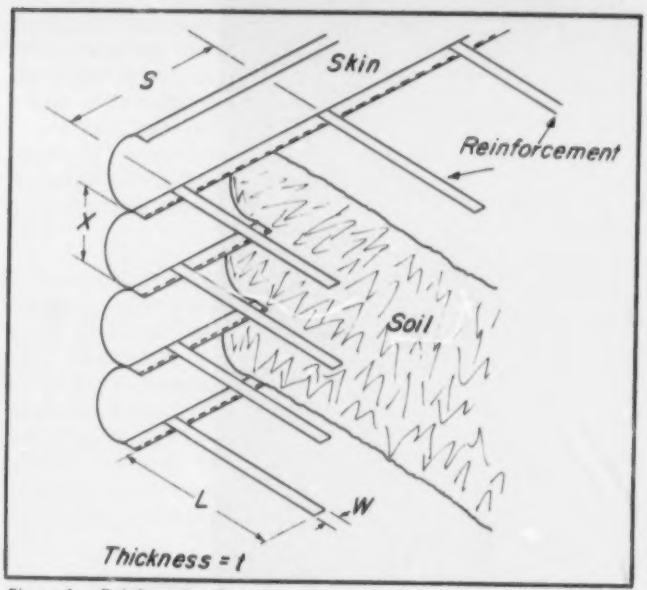


Figure 1.—Reinforced soil retaining structure.

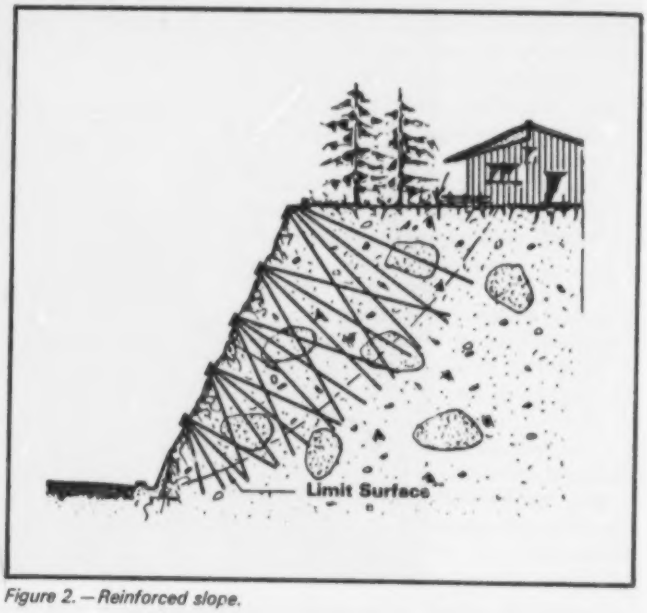


Figure 2.—Reinforced slope.

Background

Although the use of tensile inclusions in soil for reinforcement dates back several thousand years, the modern concept of soil reinforcement was proposed by Henri Vidal in 1966 in France. (*2*) The concept was first introduced in the United States in 1969 under an FHWA demonstration project on a national forest highway in California. Since then, more than 1,000 reinforced soil structures have been built throughout the United States, and more than 5,000 have been built worldwide. (*3*)

Although corrosion of the reinforcing elements always has been a serious concern, many new structures are built each year using only the sacrificial thickness design concept without additional safeguards against corrosion. Only six corrosion failures have been reported thus far; however, it is still early in the design life of most of these structures. All of the corrosion failures occurred under severe environmental conditions such as heavy salt concentrations, organic backfill soils, or other corrosive chemical attack. For example, corrosion in a wall in Spain was accelerated when a truck accident caused corrosive chemicals to penetrate the wall. A wall in Nice, France, failed when the sulfate-inducing bacteria in the organic soil used as backfill corroded the steel reinforcements. In Cap d' Agde, France, a wall failed because the aluminum alloy reinforcements contained too much copper, which crystallized during the corrosion cycle. Also, a wall in Brunswick, Georgia, that was submerged under seawater twice daily because of ocean tides failed because of localized corrosion. The backfill material exhibited low resistivity, high chloride concentrations, and the presence of heavy metals such as iron. Figure 4 shows a cross section of a metallic strip from the Brunswick wall that was reduced from 0.08 in (2 mm) to 0.05 in (1.3 mm) because of the localized corrosion. (*4*)

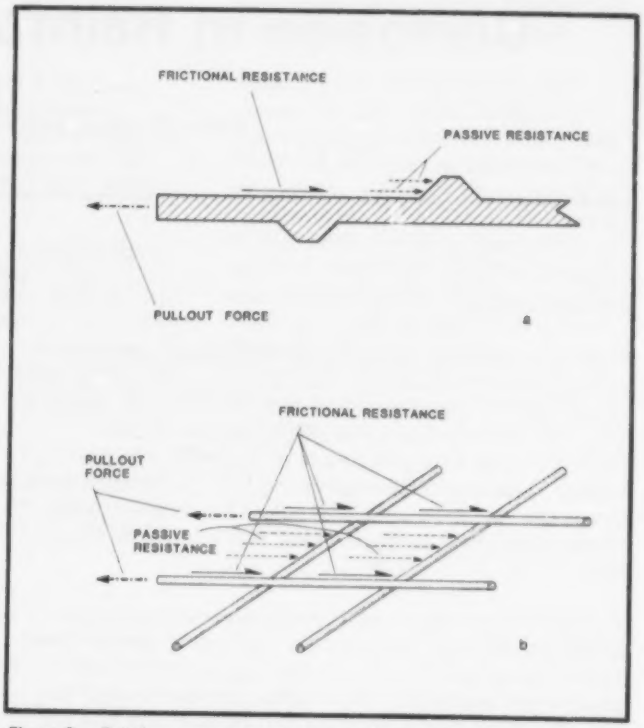


Figure 3.—Reinforcements that develop resistance by a combination of frictional and passive soil resistance. (a) Ribbed strips used in Reinforced Earth. (b) Bar mesh system.

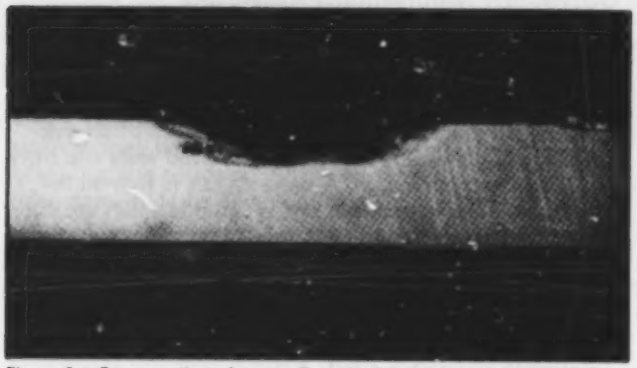


Figure 4.—Cross section of a metallic strip showing localized corrosion.

Figure 5.—Placing the major components of a reinforced soil structure.

Components of Reinforced Soil Structures

The four major components of reinforced soil structures can be seen in figure 5:

- Reinforcing elements.
- Backfill soil.
- Facing units.
- Connections between the facing units and the reinforcing elements.

Reinforcing elements

Until recently, reinforcing elements always were made of metal—mild steel with extra thick sections to allow for corrosion, stainless steel and aluminum magnesium alloys, and galvanized steel, the most commonly used reinforcing element. However, research on the performance of galvanized steel is inconclusive.

The recent emphasis on corrosion resistance has prompted the development and marketing of nonmetallic reinforcing elements made of materials such as fiberglass-reinforced plastics and geotextiles (fabrics) (fig. 6). These nonmetallic reinforcing materials do not corrode, but with time they may degrade, fracture, or be weakened by biological or environmental elements. They also are susceptible to damage from shipping, storage, and placement.

Resin-bonded epoxy coatings have been used on a few projects with some success; however, a number of problems with this method need to be resolved before it can be considered for routine application. Current research is addressing the appropriate coating thickness to minimize transportation and installation damage while maintaining sufficient flexibility. Recent research indicates that current standards for coating thicknesses (ASTM—7 to 15 mils [0.2 to 0.4 mm] and AASHTO—5 to 12 mils [0.1 to 0.3 mm]) should be increased to at least 18 mils (0.5 mm). Adhesion qualities and frictional losses associated with the use of epoxy coating also must be considered.

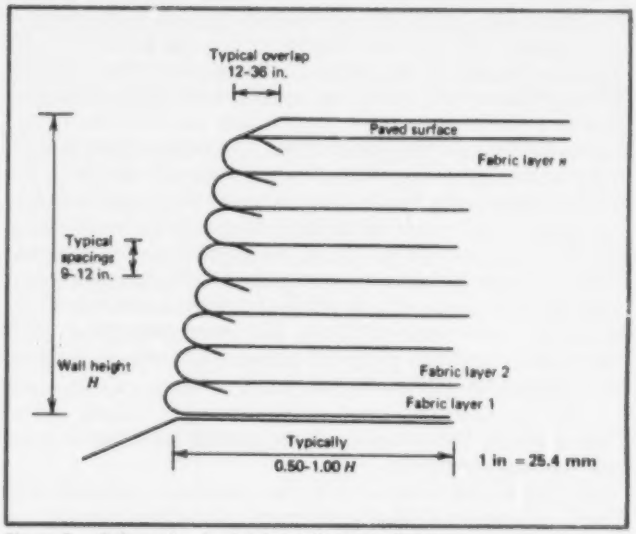


Figure 6.—Schematic of a fabric-reinforced soil wall.

Backfill soil

Backfill material usually is free-draining granular soil to provide sufficient frictional properties to maximize load transfer between the soil and reinforcement. Typical backfill specifications for reinforced soil limit the gradation, plasticity index, compaction moisture content, and organic content. FHWA specifications limit backfill to 100 percent passing the 6-in (152-mm) sieve, 75 percent passing the 3-in (76-mm) sieve, 25 percent passing the No. 200 sieve, and a plasticity index of less than 6 percent. (*5*) A prominent soil reinforcement company in France requires a minimum friction angle of 25 degrees, resistivity

of more than 33 ω·ft (1,000 ohm-cm) for unsaturated soils and 98 ω·ft (3,000 ohm-cm) for saturated soils, a pH value of 5 to 10, chloride content of less than 200 ppm, sulfate ion content of less than 1,000 ppm, and no organic content. These French limits were established from research tests that showed soil corrosivity to be controlled by the degree of saturation, porosity, acidity or alkalinity, dissolved salt content, and electrical resistivity. For example, a clay backfill usually is more corrosive to buried steel than is a clean granular soil, especially if the compaction moisture content is greater than 20 percent. Organic matter and other deleterious substances are highly corrosive to buried steel.

In addition to using free-draining soil, internal drainage systems are required to prevent localized channeling of water through the reinforced soil mass, which could cause extensive localized corrosion. Plastic sheeting and/or a clay cap also should be used over the granular mass to reduce water infiltration.

Facing units

Facing units usually are made of precast reinforced concrete panels serving mainly as architectural elements but also as a barrier to prevent the granular backfill from flowing away from the reinforcements. The reinforcement in the precast concrete panels provides strength during transportation and erection and is much less vulnerable to corrosion than are the metal reinforcements buried in the soil. Because only minor forces are exerted on the facing units, their design is based on flexibility and corrosion resistance. Metal facing panels and flexible facings such as welded wire mesh, geogrids, and geotextiles also have been used; shotcrete or gunite protective systems usually are required to stabilize flexible facing units.

Connections between the facing units and the reinforcing elements

These connections usually are made of metals prone to corrosion. A galvanized strip of steel protrudes from the concrete facing panel and is bolted with galvanized bolts to the galvanized reinforcements buried in the soil mass. The corrosive environment at the connection can be severe because the space behind the facing panels allows for large concentrations of water and oxygen. Because the metal protruding from the concrete panel forms a very active and classic galvanic cell when it is connected to the metal reinforcement buried in the soil mass, similar metals should be used to connect facing units and reinforcing elements.

Corrosion Mechanism in Metals

Corrosion results from the chemical interaction between a metal and its surrounding environment. Most soil reinforcement corrosion is essentially an electrochemical process because it usually occurs in the presence of an electrolyte, such as water, containing dissolved salts and high concentrations of oxygen. A galvanic cell is formed between two poles—an anode and a cathode—that are connected by the electrolyte to form a complete circuit (fig. 7). The conductivity of the electrolyte directly controls the quantitative loss of metal ions from the anode as the current flows from the anode through the electrolyte to the cathode and back through the metal in a complete circuit.

The conductivity usually is determined indirectly by measuring the soil's resistivity because resistivity is the direct inverse of conductivity. The cathode area does not corrode because of the deposition of hydrogen or other ions that carry the current.

Attempts have been made to eliminate or counteract the galvanic cell formation using galvanizing and cathodic protection systems. The steel galvanizing process (ASTM A123) forms a zinc coating on the metal, which becomes a sacrificial anode of the galvanic cell, leaving the base metal intact. Zinc also encourages a more uniform corrosion, reducing the formation of pits and other localized corrosion.

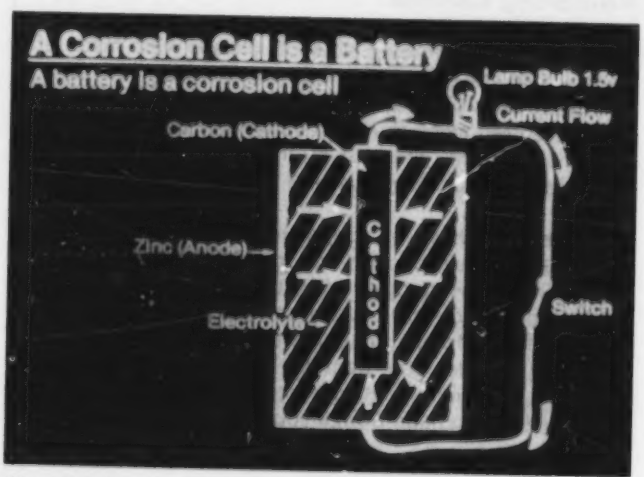


Figure 7.—Most soil reinforcement corrosion is essentially an electrochemical process.

Cathodic protection systems, on the other hand, use sacrificial aluminum anodes to divert the corrosion attack away from the steel reinforcements. Two cathodic protection systems were installed on separate structures in South Africa, and both systems failed in less than 4 years. The reasons for these failures are unknown. The systems may have been applied incorrectly, thus accelerating the corrosion, or the systems may not have been capable of reducing corrosion.

Current efforts are focused on developing a cathodic protection system for reinforced soil structures in which the cathodic protection system is connected with the entire reinforced soil mass and the connections between the reinforcing elements and the facing units. The system requires periodic maintenance and service to replace the aluminum anodes that become corroded. This system has been used successfully for protecting steel structures above ground, especially in the oil industry; however, it is not yet popular in the reinforced soil area because of the extra initial cost and recurring maintenance costs.

Another method that has not yet been applied involves encapsulating a coated or galvanized reinforcing element into a durable synthetic sheathing to produce a double protection system similar to that used to protect permanent ground anchors. (*6*) The encapsulated synthetic sheathings could be manufactured with studs, grooves, or corrugations on the exterior surface to satisfy the frictional strength requirement. The connections at the facing units could be encapsulated in the same way as the strips, straps, wires, or grids buried in the soil mass.

The major drawback to this double corrosion protection system is cost. With permanent ground anchors, the relative isolation or low density of the anchors keeps the cost down, but the high density of reinforcing elements in a reinforced soil mass has discouraged the use of double protection systems. Also, as mentioned previously, the durability of the synthetic material used for the sheathing is questionable because it may fracture or weaken with time and is susceptible to damage from shipping and placement.

Another form of corrosion, stray-current corrosion, can occur from electrical leaks into the reinforced soil mass. The stray currents enter the metal reinforcements and are discharged back into the soil at a distant point. The corrosion occurs where the current leaves the metal and enters the soil or water electrolyte.

The corrosion mechanism is a complicated, unpredictable interrelationship of many factors, some of which change with time. Because it is unlikely that a "magical alloy" that can resist aggressive corrosive attack will be developed, progress must continue to be made in predicting the corrosive environment and in developing protective coatings with a predictable service life. The rate, extent, and consequences of corrosion of reinforced soil elements also must be understood to determine the service life of a reinforced soil structure.

FHWA Corrosion Study

FHWA has initiated a research study to evaluate the potential corrosion problem in reinforced soil structures and to seek appropriate solutions. Any investigation may conclude that failure of a reinforced soil structure was caused by corrosion, because an examination of the reinforcement embedded in the soil almost always will show some signs of corrosion. (*7*) However, corrosion may not be solely responsible for the failure.

Pit-type penetrations of a buried strip or even complete severence of the strip does not necessarily lead to failure of a reinforced soil structure as it would for a buried tank or pressure vessel. Depending on the number and location of the pitting-type penetrations, the serviceability or the effective cross section resisting capacity may not have been dangerously reduced.

In the FHWA study, the corrosion and deterioration mechanisms and rates in reinforced soil structures are being evaluated through laboratory and field experiments. Specifications will be developed, and new test methods for analyzing and selecting backfill and reinforcement materials will be evaluated.

Facing panel materials, backfill soils, and reinforcing elements will be examined to determine which factors affect the design life under corrosive and deteriorating forces commonly encountered in reinforced soil environments. Chemical composition of backfill soil, kind of backfill (granular or clay), protective coating types, and stray currents will be evaluated. Exposure to seawater, roadway deicing salts, and galvanic current also will be studied, as will the potential for using cathodic protection systems and other methods currently used on highway bridge decks, underground pipelines, and piles to minimize the harmful effects of corrosion.

The long-term corrosion rate and/or durability of four field structures, both new and existing, will be monitored. Current methods for evaluating backfill materials will be studied and, if appropriate, new test methods for the analysis of pH, resistivities, sulfates, and chlorides will be developed. The effect of using lower quality backfill materials on the design life of a reinforced soil structure also will be evaluated.

Laboratory and field experiments will be conducted to develop appropriate requirements for selecting, storing, handling, and installing epoxy-coated reinforcing elements and geosynthetics (geotextiles and geogrids) for use in reinforced soil structures. The fusion-bonded epoxies will be studied to evaluate required coating thickness, bond test criteria, impact resistance, and coating flexibility. Geosynthetics will be studied to evaluate long-term creep under sustained tensile load, resistance to chemicals and solvents under stressed conditions (environmental stress cracking), construction effects, aging, ultraviolet light degradation, and probability of nonductile failure.

Based on the laboratory and field results, a detailed manual of practice containing specifications, test methods, and engineering guidelines will be developed.

Summary

Soil reinforcement has become an effective engineering solution for many highway applications. Corrosion of metal reinforcements and durability of nonmetallic reinforcements are primary concerns in selecting and designing reinforced soil structures. The exact mechanisms of corrosion and loss of durability of soil reinforcing elements are not well understood. Cathodic protection systems, galvanized metal elements, epoxy coatings, and nonmetallic materials have been used to reduce corrosion of steel reinforcement. Double protection systems, such as encapsulating coated strips with durable synthetic sheathings, also have been proposed.

Testing and evaluation are underway to develop a clear understanding of the corrosion/durability problem and to develop design and construction guidelines for reinforced soil structures.

REFERENCES

(1) J.K. Mitchell, W.C.B. Villet, and A.F. DiMillio, "Soil Reinforcement for Stabilization of Earth Slopes and Embankments," *Public Roads,* vol. 48, No. 3, December 1984, pp. 88-95.

(2) H. Vidal, "The Principle of Reinforced Earth," Highway Research Record No. 282, *Highway Research Board,* Washington, DC, 1969, pp. 1-16.

(3) J.K. Mitchell and J.C. Collin, "Earth Walls," Proceedings of the National Academy of Engineering, 1983 Symposium on Cutting Edge Technologies, *National Academy Press,* Washington, DC, 1984.

(4) S. Frondistou-Yannas, "Corrosion Susceptibility of Internally Reinforced Soil Retaining Structures," Report No. FHWA/RD-83/105, *Federal Highway Administration,* Washington, DC, January 1985.

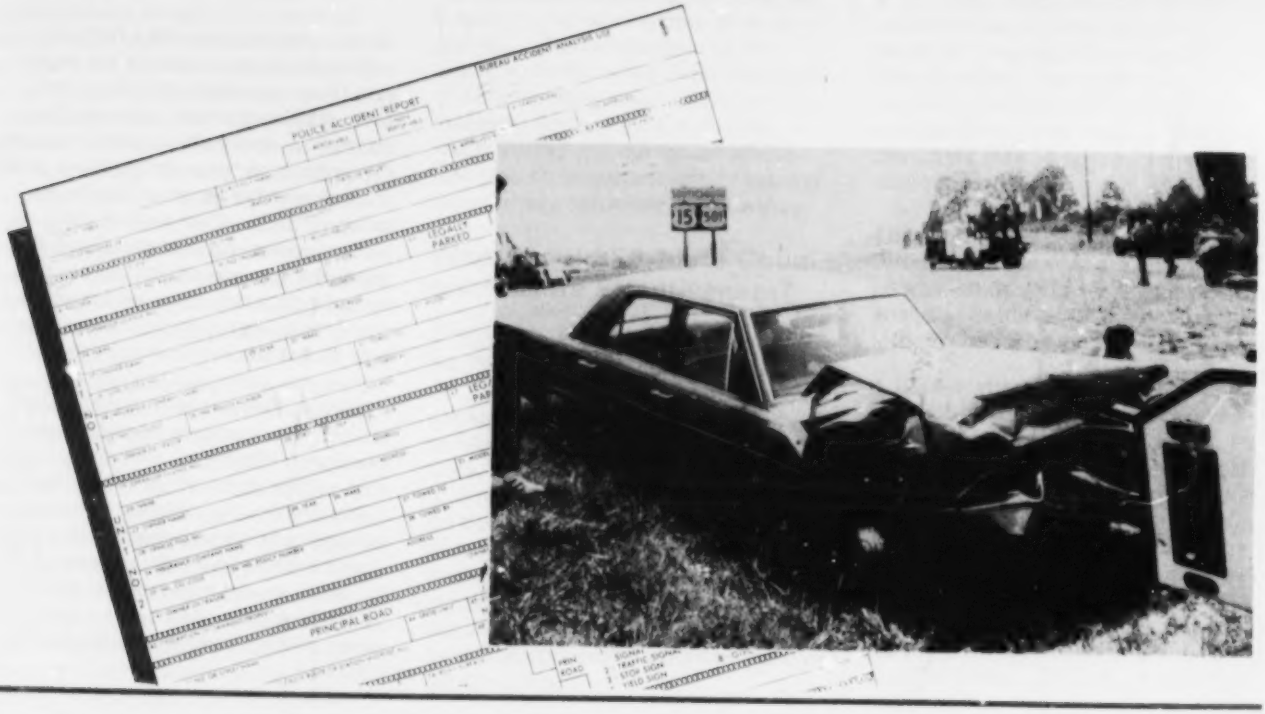
(5) "Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects," FP-85, *Federal Highway Administration, U.S. Department of Transportation,* Washington, DC, 1985.

(6) S.D. Ramaswamy, K.Y. Yong, and S.K. Roy, "Corrosion Protection of Ground Anchors," Proceedings of 3d Asian Pacific Corrosion Control Conference, Taipei, Taiwan, June 1983.

(7) S.D. Ramaswamy, K.Y. Yong, and S.K. Roy, "Corrosion Aspects of Reinforced Earth," Proceedings of 3d Asian Pacific Corrosion Control Conference, Taipei, Taiwan, June 1983.

Salem D. Ramaswamy is an associate professor in the Department of Civil Engineering at the National University of Singapore. He has over 20 years of experience in teaching, consulting, and research in geotechnical engineering and highway materials. He has been involved in soil stabilization projects and has published over 100 papers on geotechnical engineering, corrosion in geotechnics, and highway materials. Dr. Ramaswamy was on sabbatical working for FHWA in the Materials Division on geotechnical projects when he co-authored this article.

Albert F. DiMillio is a geotechnical research engineer in the Materials Division, Office of Engineering and Highway Operations R&D, FHWA. Mr. DiMillio is project manager for FCP Project 5P, "Foundations and Earth Structures." Before his present position, he served as an area engineer in FHWA's Indiana Division Office and as the Regional Geotechnical Specialist in Region 5, Homewood, Illinois.



Toward Improved Highway Safety Analysis

by
Charles P. Brinkman

Introduction

The fatality rate per 100 million vehicle-miles of travel has decreased from over 18 to under 3 (11.2 to 1.9 fatalities per 100 million vehicle-kilometers of travel) over the past 60 years (fig. 1) (*1*)[1]—an average decrease of over 3 percent per year. Although traffic safety has improved noticeably over the years, efforts to quantify the extent that various factors have contributed to this improvement have not been definitive. The dramatic decline in fatality rates results partly from advances in medical treatment and improvements to vehicles and highways; seatbelts save lives, and newer highways are safer than older ones. Part of this improvement, however, may result from factors associated with the changes in the kind of vehicle-miles of travel. For instance, the percentage of urban travel, which is associated with a fatal accident rate only one-half as great as the rural fatal accident rate, has increased.

Changes in driver demographics as the "baby boom" generation ages also may have contributed to a lower fatal accident rate as perhaps drivers are more safety-conscious today. Finally, economic factors have a short-term influence on traffic accident rates by influencing the amount of various kinds of travel. For example, teenage unemployment might reduce the amount of driving by teenagers and thus reduce traffic fatalities.

In the past, highway safety hazards were relatively easy to identify, and many of the most hazardous situations now have been improved. Despite this improvement, 44,372 persons died and more than 3,200,000 persons were injured in motor vehicle accidents in 1984. The estimated cost including property damage was over $100 billion. (*2, 3*) The economic loss amounted to approximately 2 percent of the gross national product. Today, with tight budgets and a vast highway system, available safety funds must be spent even more wisely. To ensure this, more effective means for identifying hazardous situations and more accurate estimates of the effectiveness of candidate safety improvements are needed. This article outlines some of the major obstacles in current practice to improved highway safety analysis and suggests methods for improvement.

[1] Italic numbers in parentheses identify references on page 54.

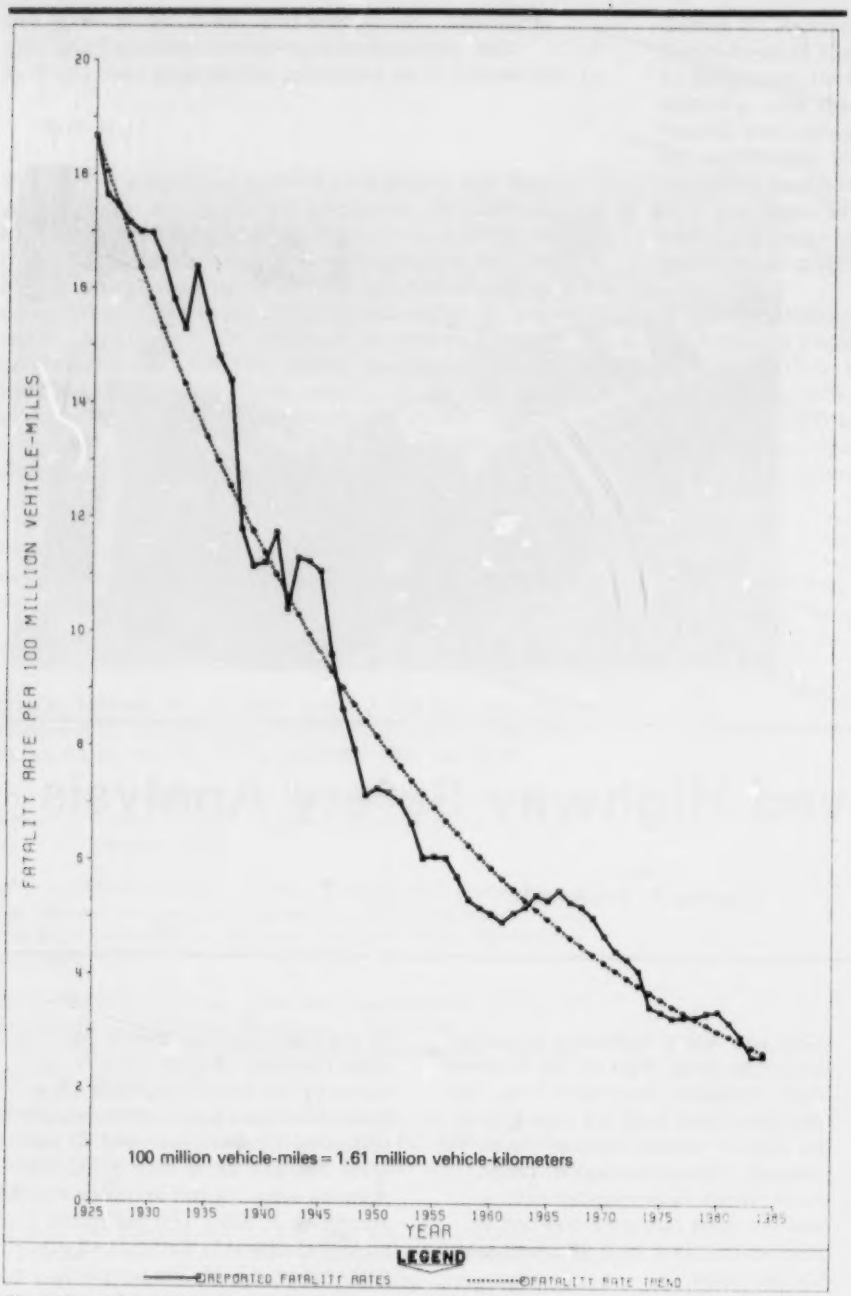


Figure 1. – U.S. motor vehicle traffic fatality rates (1925-1984). (1)

Information Needs

The ready availability of accurate and complete data is of paramount importance to improved highway safety analysis. At the national level, traffic volumes, the physical condition of the highway system, and trends in highway safety are important for establishing policy priorities and determining future needs. At the State and local levels, similar policy decisions are made. In addition, efficient day-to-day operation of the highway system demands detailed information about specific highway sites for maintenance, traffic management, and safety.

File linkage

Safety analysis uses data from a variety of sources, usually on separate files—accident and driver records, traffic volumes, highway characteristics, and traffic control devices. File linkage of these data allows great opportunity for improved highway safety analysis. Coordinated data collection avoids duplication. Carefully considering compatibility and quality reduces data collection and management costs and provides better support to the decisionmaking process.

Although file linkage unquestionably is desirable, it entails considerable obstacles. Ideally, all files should be compatible; in practice, little effort is made among the different offices of an organization responsible for data collection to ensure data compatibility. Most importantly, different location reference systems often are used, making linkage extraordinarily tedious.

Despite these obstacles, several States already have made strides in file linkage; several other States currently are merging data files with the encouragement of and, in several instances, partial financial support from the Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration.

Problems with safety information

State recordkeeping systems have severe shortcomings. Despite the wealth of data available in various files, information about the roadside and highway horizontal and vertical alignment, for example, usually does not exist in computerized form and is difficult to obtain. Highway inventory information is very limited for off-State systems, making computerized linkage of accidents to specific highway characteristics impossible.

Another problem is the quality and completeness of data. For example, not all reportable accidents get reported, particularly in urban areas where property-damage-only accidents often are not reported. In general, the more severe an accident, the more likely that accident will be reported. Also, a multi-vehicle accident is more likely to be reported than a single-vehicle accident of equal severity. Accidents are probably less likely to be reported during bad weather than during good weather.

Disregard for discrepancies in reporting particular accident types can lead to erroneous conclusions, and any safety analysis must consider the implications of these discrepancies. For example, a roadside appurtenance might reduce the severity of a majority of impacts to the extent that only minor damages and minor or no injuries result, and thus these accidents often would not be reported. The few severe accidents would likely be reported. If effectiveness were measured only by the percentage of reported accidents resulting in fatalities or severe injuries, it might be concluded that the appurtenance is ineffective. However, overall the appurtenance is effective.

The availability of complete, quality data, however, does not ensure good analysis. The nature of the highway accident problem makes data analysis and interpretation difficult. Statistical analysis is severely handicapped without sound experimental design, which usually is not considered when highway safety projects are selected for implementation. Another problem is the interrelationship of accident causal factors, confounding the establishment of strong statistical relationships. Therefore, although accident studies quantify the extent of a particular problem and provide valuable insight, they can only provide general guidance to specific safety design decisions because of their many limitations.

Safety design decisions also must be based on engineering standards and practice, physical analysis of the problem, traffic operational measures of effectiveness, and human factors research. For example, full-scale crash testing and computer simulation play an important role in examining roadway hardware performance.

Who Should Evaluate Countermeasure Effectiveness?

A thorough knowledge of experimental design, data quality, inferential statistics, and data interpretation are among the factors essential to conducting highway safety evaluations. A review of the current literature reveals that accident studies with serious design flaws and inadequate or inappropriate statistical analysis are commonplace. The studies often are inconclusive or provide conflicting conclusions, leaving users with little guidance concerning countermeasure effectiveness.

Therefore, trained professionals should determine countermeasure effectiveness instead of operations personnel who, for the most part, have neither the time nor training to conduct effectiveness evaluations. However, the practitioner is responsible for monitoring a countermeasure to ensure that it meets its objectives.

Experimental Designs

FHWA sponsored the development of an accident research manual (*4*) and presented several workshops aimed at improving accident research. The manual and workshops warned of the following dangers inherent in simple before/after evaluations:

- They do not rule out rival explanations.
- If only two time periods are examined, longer term trends go unnoticed.
- They may lead to overestimates of countermeasure effectiveness as a result of "regression to the mean." Simply stated, sites with the highest number of accidents in the past are most likely to have fewer accidents in the future even if no countermeasures are installed.

These problems can be minimized through the use of more effective experimental design or imaginative analysis. Better experimental designs include the following (*4*):

- Before/after designs with randomized control groups—This design is the strongest before/after design. Candidate locations for a given treatment are randomly assigned to either a treatment group or a control group. Controls can be imposed without using additional locations. For example, accidents during a certain period of the day, week, or year may be compared with those occurring during another period. Similarly, a specific accident type may be compared with another accident type.
- Before/after designs with comparison groups—Control locations are sought that are as similar as possible to the locations treated to diminish some of the problems inherent in simple before/after designs. An adjacent highway section often is a good control.
- Time series designs—Numerous observations of the variable of interest are made over a period of time. However, there must be sufficient data for the variable to be stable for each time period.

Simple before/after studies without controls should be discouraged. If a sound experimental design is not possible, the following should be considered: Monitoring from an operational perspective only; using measures of effectiveness (for example, traffic conflicts, speed differentials, or lateral placement) instead of accidents, to supplement accidents, or to help serve as a control; and/or using less traditional statistical methods such as Bayesian statistics. Statistical techniques, although useful, are no substitute for good experimental design.

Empirical Bayesian Statistics

Recent research sponsored by FHWA in conjunction with the National Highway Traffic Safety Administration and Transport Canada proposed using empirical Bayesian statistics for highway safety analysis. (*5*) This method combines current experience with prior experience and thus partially overcomes the lack of sufficient statistical significance in individual accident studies to conclude that a safety measure is effective. Empirical Bayesian statistics also avoid inflated estimates of safety measure effectiveness resulting from the regression-to-the-mean phenomenon.

In the FHWA study, empirical Bayesian statistics were used to estimate the number of accidents for a site (i) by adjusting the observed accident record for that site with the accident experience of similar sites as follows:

$$m = x_i + (\bar{x}/s^2)\ (\bar{x} - x_i)$$

Where,

x_i = accident experience at each site i.
$\bar{x}$ = the mean from a group of sites similar to site i.
s^2 = the variance from a group of sites similar to site i.

The Bayesian estimates for the before-accident experience at the individual sites were summed and compared with the observed after-accident experience to determine safety measure effectiveness. The assumption is that the empirical Bayesian estimate of accident experience is a better estimate of the true safety of the sites than is the observed (sample) accident experience. However, it is not yet agreed upon as to under what circumstances Bayesian statistics should be proposed as an alternative to the use of classical statistics for evaluating countermeasure effectiveness.

Table 1 illustrates the use of this method for two-way to four-way stop conversion in San Francisco, California.

Incremental Effectiveness

Another difficulty in determining countermeasure effectiveness is the tendency to install several countermeasures at the same site at the same time. Because countermeasures often may be effective against the same kinds of accidents, their effect is not necessarily additive. Some countermeasures while ineffective alone may enhance the effectiveness of another countermeasure. Very few, if any, countermeasures eliminate or reduce all kinds of accidents. When sufficient accident data are available, the selection of countermeasures should be based on an analysis of that data categorized by kind of collision, accident severity, time of day, and environmental condition.

Table 1.—Safety measure effectiveness evaluation using Bayesian statistics

Accident type	Actual number of before accidents	Actual number of after accidents	Apparent percent effectiveness[1]	Bayesian estimate of number of accidents without countermeasure	Unbiased percent effectiveness[2]
Right-angle	129	16	88	93	83
Rear end	10	16	−60	4	−300
Left turn	14	7	50	10	30
Pedestrian	6	2	67	6	67
Injury	48	9	81	35	74
Total number of accidents[3]	172	50	71	130	62

[1] The actual number of after accidents subtracted from the actual number of before accidents divided by the actual number of before accidents.

[2] The actual number of after accidents subtracted from the Bayesian estimate of accidents divided by the Bayesian estimate of accidents.

[3] Not all accident types are shown.

A recent FHWA study concluded that it is desirable to determine the incremental effectiveness of a countermeasure used with another countermeasure. (*6*) Such determinations are particularly necessary to avoid implementing combinations of countermeasures that result in less than optimal safety improvements. The need for gradually introducing improvements at individual sites or the large number of similar sites required make such determinations difficult. Improved highway information systems eventually might overcome some of these problems; the unavailability of computerized data on countermeasure implementation (for example, date, location, and kind of countermeasure) currently prevents tapping large historical accident data bases for determining countermeasure effectiveness. Sample size requirements, however, always will place a limit on detecting small incremental differences in effectiveness.

Interpretation of Analysis

Computers have made it easy to establish mathematical relationships between traffic accidents and various factors; however, it is possible to arrive at chance relationships. Also, a strong mathematical relationship that exists between various factors does not necessarily indicate a causal relationship. (*7*) In analyzing highway accident data, a multitude of possible causative factors often are interrelated and sometimes difficult to quantify. For example, one study found that on arterial street segments, the mean accident rate is significantly lower on segments with fewer than three regulatory sign faces. The authors did not conclude, however, that regulatory signs contribute to accidents. (*8*)

Applicability of Evaluation Results

States often are reluctant to accept accident countermeasure effectiveness evaluations found in other States. If driver, vehicle, highway, environment, and accident reporting factors are accounted for properly and sample size is sufficient, effectiveness measures should be generally applicable. Indeed, the larger and perhaps even more varied the data base, the more reliable the estimates of countermeasure effectiveness. Although in an initial study on countermeasure effectiveness similar test sites might be selected carefully, subsequently the countermeasure is not likely to be applied to sites as similar as the test sites. Thus, a national estimate using data from several States actually may provide a better estimate of effectiveness over the long term than one based on data from one State.

Exact measures of countermeasure effectiveness are unrealistic. The variability between similar sites is so large that even if the average effectiveness is accurately determined, the effectiveness at a particular site is likely to be quite different from the average. Indeed, it is important to determine countermeasure effectiveness accurately enough to support the use of effective countermeasures and to avoid widespread use of accident countermeasures that are ineffective or misapplied. Engineers, however, should expect only general guidance on countermeasure effectiveness. Eventually, research should be able to provide ranges of expected effectiveness for various safety measures and factors that tend to increase or decrease this effectiveness.

Summary

A vast quantity of data potentially useful for highway safety analysis is collected regularly by the States and maintained as distinct data bases for a variety of purposes. The annual national cost of all highway, vehicle, and driver data collection and maintenance is approximately $1 billion. Safety considerations alone could not justify collecting and maintaining all this information. For a more thorough analysis, States may create comprehensive computerized safety record-keeping systems by merging data from various data bases with their accident data. An information system created from data merged from several States would provide, at a reasonable cost, the information needed for most general safety analyses of interest to FHWA.

Despite the limitations to what can be learned from the analysis of traffic accident data, rigorous analysis using both careful experimental design and proper statistical methodology can make a vital contribution to highway safety.

REFERENCES

(1) "Highway Safety Performance—1984: Fatal and Injury Accident Rates on Public Roads in the United States," *Offices of Highway Safety and Highway Information Management, Federal Highway Administration,* Washington, DC, January 1986.

(2) "Accident Facts," *Statistics Department, National Safety Council,* Chicago, IL, 1985.

(3) B.C. Kragh, T.R. Miller, and K.A. Reinert, "Accident Costs for Highway Safety Decisionmaking," *Public Roads,* vol. 50, No. 1, June 1986, pp. 15-20.

(4) F.M. Council et al., "Accident Research Manual," Report No. FHWA/RD-80/016, *Federal Highway Administration,* Washington, DC, February 1980 (PB No. 81 155152).[2]

(5) E. Hauer, J. Lovell, and B.N. Persaud, "New Directions for Learning About Safety Effectiveness," Report No. FHWA/RD-86/015, *Federal Highway Administration,* Washington, DC, January 1986 (PB No. 86 180759).

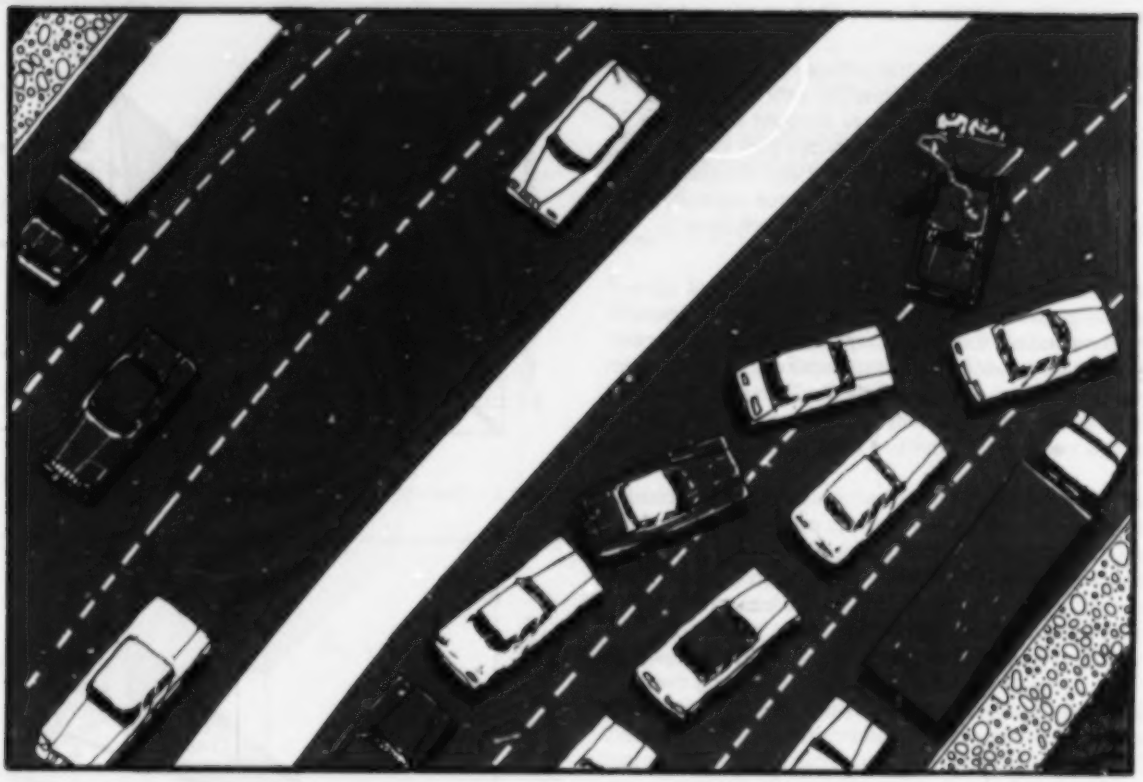
(6) H.D. Robertson and K.S. Opiela, "Feasibility of Determining the Incremental Effectiveness of Accident Countermeasures," Report No. FHWA/RD-85/043, *Federal Highway Administration,* Washington, DC, February 1985 (PB No. 86 188984).

(7) P.G. Hoel, "Introduction to Mathematical Statistics," *John Wiley & Sons, Inc.,* New York, NY, 1962, pp. 164-165.

(8) T.K. Datta, M.R. Parker, Jr., and D.A. Randolph, "Analysis of Urban Arterial Road and Street Accident Experience," Report No. FHWA/RD-82/137, *Federal Highway Administration,* Washington, DC, September 1982, p. 92 (PB No. 85 184448).

Charles P. Brinkman is a project manager in the Traffic Safety Research Division, Office of Safety and Traffic Operations Research and Development, FHWA. He is involved in research to improve highway safety evaluation.

[2] Reports with PB numbers may be purchased from the National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161.



Analytical Procedures for Estimating Freeway Traffic Congestion

by
Juan M. Morales

Introduction

A freeway incident—an accident, stalled vehicle, spilled load, or any other event that reduces the normal capacity of the roadway—causes motorist delay. Freeway incident management techniques are directed at reducing this delay, which varies with traffic volume, number of lanes, and the duration of the incident.

The Federal Highway Administration (FHWA) funded research in the late 1970's to develop guidelines and recommendations to help highway departments, police agencies, and other organizations select, plan, design, and implement low-cost measures to deal with incidents that cause freeway congestion. The research results were published in a six-volume report, which presented an overview of the nature and magnitude of the freeway incident management problem and summarized possible solutions. (*1*)[1] An analytical procedure to estimate traffic delay and congestion and assess the tradeoffs in cost-effectiveness among many alternative measures also was included in the reports. Computational examples and delay, time, and queue tables for typical conditions were provided.

This article summarizes the basic analytical procedures presented in these reports and describes a new, user-friendly microcomputer model for quickly and easily computing delay, time-to-normal flow (TNF), and maximum queue (Q_{max}) caused by freeway incidents.

[1] Italic numbers in parentheses identify references on page 61.

Representation of Incident Delay

The procedures presented in this article rely heavily on the development of a simple technique for estimating total vehicle-hours of delay. Any freeway incident can cause delay by reducing the number of vehicles that can pass the incident in a given period of time. Even vehicles removed to the freeway's shoulder will reduce capacity as motorists slow to stare at the emergency activities.

To quantify this delay, traffic volumes and incident durations can be graphically represented, as shown in figure 1. The horizontal axis is a timeline indicating the occurrence of incident-related events and the overall duration of their impact on traffic flow. The vertical axis is the cumulative traffic volume—the sum of the vehicles passing any given point on the freeway in a defined time period.

The demand flow or volume—the total number of vehicles using the freeway at a given time—is represented by the slope of L1. When an incident occurs (Time A), the reduced roadway capacity (L2) is less than the demand flow because of a lane blockage. This reduced capacity remains in effect until the incident is cleared from the freeway (Time B). At that time, the queued traffic can begin to flow at a "getaway" capacity (L3) approaching the freeway's capacity. When the last vehicle in the queue reaches the normal flow speed and traffic resumes flowing at the demand volume (Time C), the effects of the incident are over.

The getaway capacity, or the rate at which vehicles can depart a standing queue, is, in some cases, less than the typical capacity rate (under ideal conditions) of 2,000 passenger cars per hour per lane (pcphpl). Various observations of freeway getaway rates range from as low as 1,500 pcphpl to as high as 2,000 pcphpl. (*2-4*) Local driving characteristics have a major influence on this range. The analytical procedures described in this article assume the getaway capacity to be equal to the freeway's capacity.

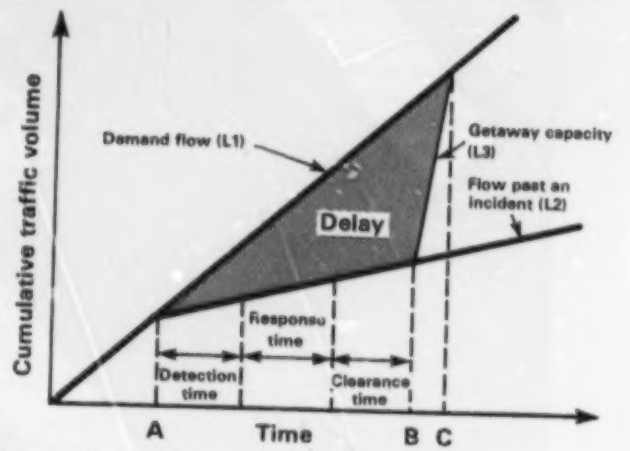


Figure 1.—Quantifying delay caused by a freeway incident.

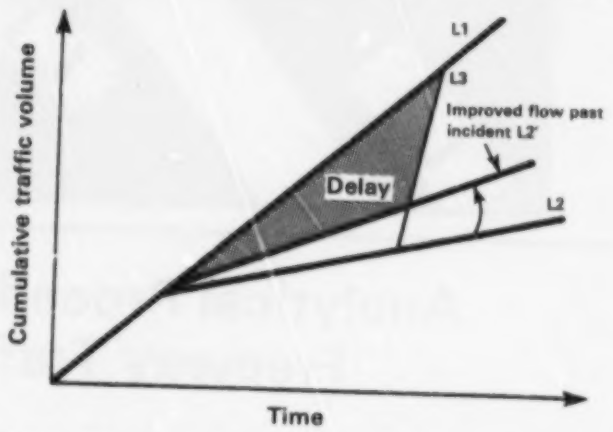


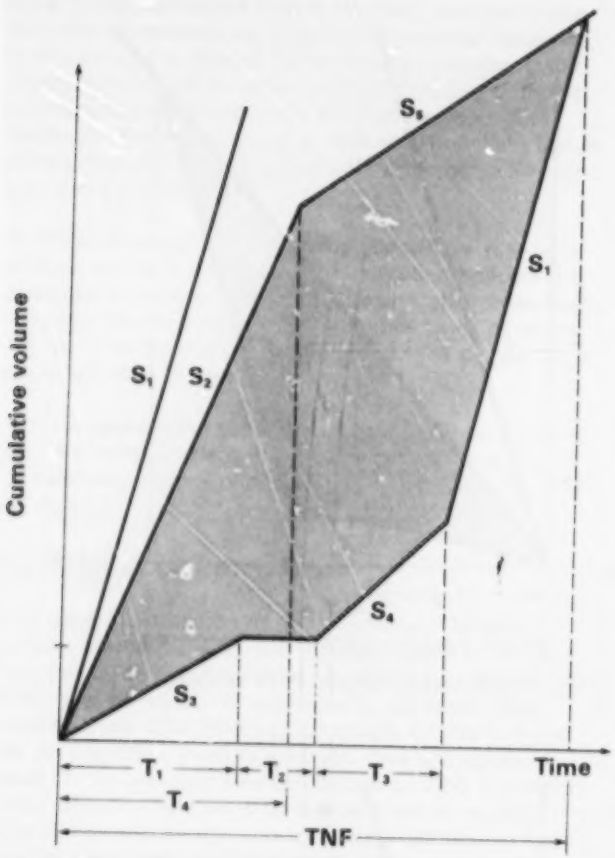
Figure 2.—Delay reduction caused by increasing flow past the incident.

Factors Affecting Incident Duration

A number of factors determine the magnitude of incident-caused delay, which is represented by the shaded area in figure 1. Only some of these factors can be influenced by freeway incident management techniques. Other factors, such as the freeway's capacity and demand flow, generally are fixed by external environmental circumstances such as the number of lanes and time of day. Unless an incident occurs just before or at the end of a peak period or traffic is diverted during an incident, the demand flow rate is assumed to remain constant for the duration of the incident.

Two factors that can be influenced by incident management techniques are the reduced capacity past the incident and the incident's total duration. Effective onsite traffic management techniques optimize use of whatever freeway capacity remains after the incident. Graphically, this is represented in figure 2 by an increase of the slope of the reduced roadway capacity L2 to create an improved flow rate L2'.

Another factor influencing total delay is the time from the moment the incident occurs to the time it is cleared from the freeway. This time interval AB can be expressed as the sum of the detection, response, and clearance times as shown in figure 1. Obviously, minimizing any of these times through efficient incident management will result in less total delay.



S_1 = Capacity flow rate of the freeway, veh/hr.
S_2 = Initial demand flow rate, veh/hr.
S_3 = Initial bottleneck flow rate, veh/hr.
S_4 = Adjusted bottleneck flow rate, veh/hr.
S_5 = Revised demand flow rate, veh/hr.
T_1 = Incident duration until first change, min.
T_2 = Duration of total closure, min.
T_3 = Incident duration under adjusted flow, min.
T_4 = Elapsed time under initial demand, min.
TNF = Total elapsed time until normal flow resumed, min.

Figure 3.—General condition diagram.

Procedures for Estimating Delay

Delay can be estimated for a variety of incident management situations from a general condition diagram (fig. 3). From this diagram, the following equation for computing delay can be derived:

$$\begin{aligned}\text{Total delay} = [&T_1^2(S_1 - S_3)(S_5 - S_3) + T_2^2 S_1 S_5 \\ &+ T_3^2(S_1 - S_4)(S_5 - S_4) \\ &- T_4^2(S_1 - S_2)(S_2 - S_5) \\ &+ 2T_1T_2S_1(S_5 - S_3) \\ &+ 2T_1T_3(S_1 - S_4)(S_5 - S_3) \\ &+ 2T_1T_4(S_1 - S_3)(S_2 - S_5) \\ &+ 2T_2S_5(S_1 - S_4) \\ &+ 2T_2T_4S_1(S_2 - S_5) \\ &+ 2T_3T_4(S_1 - S_4)(S_2 - S_5)]/2(S_1 - S_5).\end{aligned}$$

Similarly, an expression for the TNF can be written as follows:

$$TNF = [T_1(S_1 - S_3) + T_2S_1 + T_3(S_1 - S_4) + T_4(S_2 - S_5)]/(S_1 - S_5)$$

The general equation to compute the maximum queue, Q_{max}, is somewhat more complicated and is indicated as follows:

$$Q_{max} = T_aS_2 + T_bS_5 - T_cS_3 - T_dS_4 - T_eS_1.$$

T_a, T_b, T_c, T_d, and T_e are functions of the conditions being considered and vary accordingly. However, by definition queue is the algebraic difference between the demand flow L1 and the bottleneck flow L2 at a specific time (figs. 1 and 2). Therefore, Q_{max} can be obtained graphically by computing the maximum difference between L1 and L2.

It should be noted that these expressions do not apply to every imaginable delay condition and should be used carefully. Four specific delay conditions (fig. 4), obtained from the general diagram (fig. 3) for estimating vehicle-hours of delay, are typical. In these conditions, either the demand flow rate or the reduced flow rate changes because of varying incident circumstances.

In Condition 1—simple blockage—the number of vehicles that would have gone through a point if the incident had not occurred (the demand flow) is indicated by S_2. The actual number of vehicles going through this point at the reduced flow rate is shown as S_3. The duration of the incident, from the time of occurrence until the time of clearance, is represented by the time interval T_1. After the incident has been cleared, the queue of vehicles delayed by the incident will move past the point at a getaway capacity S_1 (assumed to be equal to the freeway capacity). Traffic will continue to flow at this rate until all queued vehicles have gone through—at TNF.

The shaded area shown in Condition 1 represents the total vehicle-hours of delay for all the vehicles affected by this incident. Delay will be accumulated whenever the reduced flow rate S_3 is lower than the demand flow rate S_2.

Condition 2 is similar to Condition 1 but includes a short-term closure on the affected freeway. The time interval T_2 indicates that the freeway is completely closed and that no vehicles can go through the incident point. Vehicle-hours of delay continue to accumulate as more vehicles join the queue forming behind the closure.

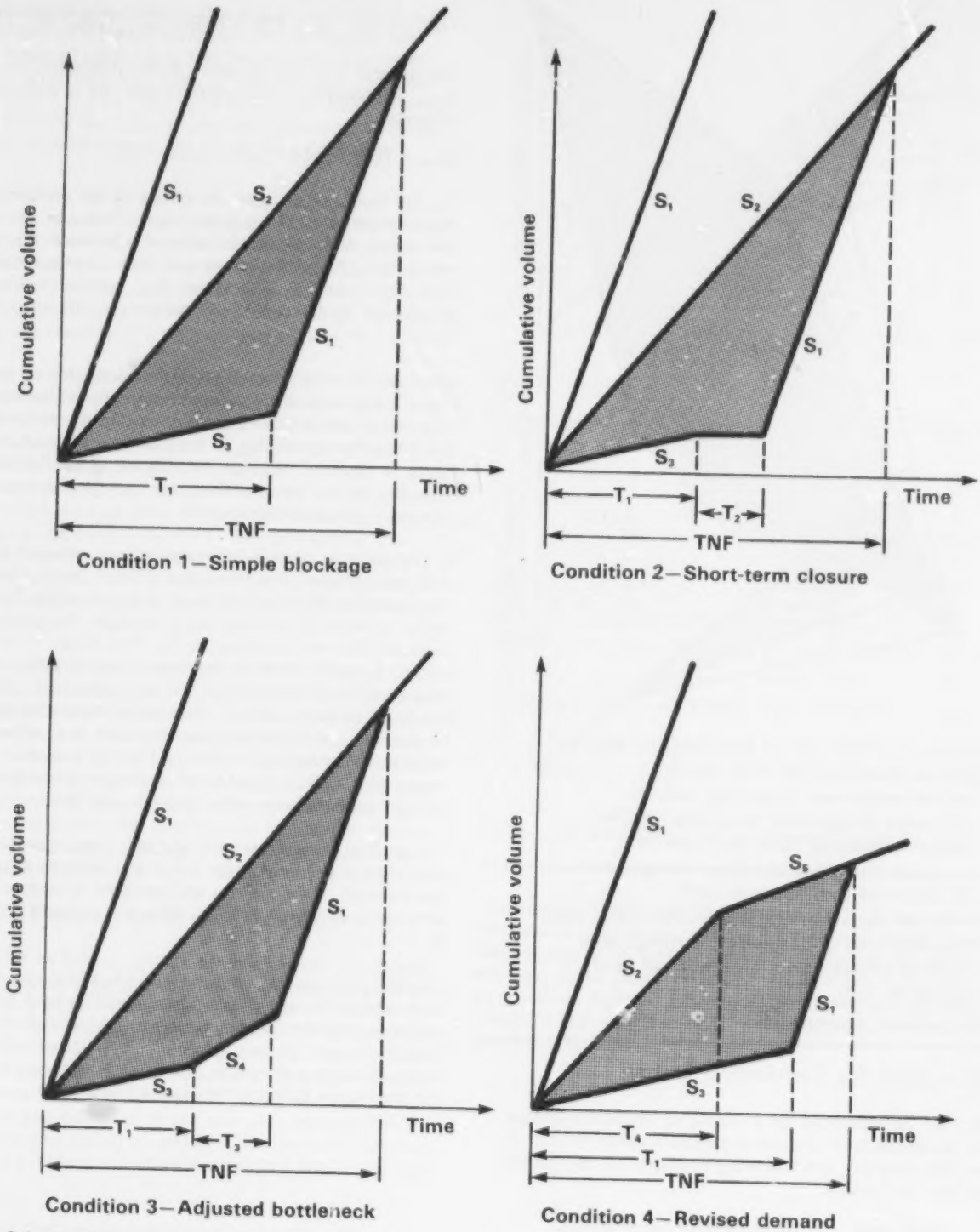


Figure 4.—Delay conditions.

Condition 3 is similar to Condition 2 except at the time interval T_1 the bottleneck flow is adjusted, and the onsite flow rate is increased for a period before total clearance by improving the flow of traffic through effective traffic management (such as police officers directing traffic) or by reopening lanes previously blocked by debris and wreckage. The time interval T_3 indicates how long this improved flow rate S_4 is in effect before the getaway capacity S_1 can be attained.

Condition 4 is created when the demand flow rate S_2 is reduced during the incident. This condition typically is caused by natural or artificial upstream traffic diversion or by typical fluctuations in traffic volumes, such as those that occur at the end of a peak period. The demand flow rate drops from S_2 to S_5 at time T_4.

With the appropriate substitutions, these four conditions can, of course, be derived from the general equations. For example, under Condition 1, $T_2 = T_3 = T_4 = 0$, $S_4 = S_3$, and $S_5 = S_2$.

Application of Procedures

Total delay is a function of three variables: Remaining capacity, traffic demand, and incident duration. At least three and up to five flow rates (depending on delay conditions) must be known or estimated to calculate delay. Some of these flow rates can be measured easily in the field for particular freeway sections. Average volumes based on historic data also can be used. Table 1 presents typical capacity flow rates S_1 and bottleneck capacity flow rates S_3 for both in-lane and shoulder incidents for freeways of two, three, and four lanes. (*1*)

Once the necessary flows and durations are known, total delay, TNF, and Q_{max} are computed by solving the general equations presented previously or by using the interactive spreadsheet. The spreadsheet uses LOTUS 1-2-3 running on an IBM-compatible microcomputer with at least 128k of memory. The program interactively guides the user through a series of screens to enter the required data (flows and incident durations) and computes the total delay, TNF, and Q_{max}. In addition, the delay condition being specified is graphically displayed. The results and graph can be printed as well.

Individual entries can be changed to determine the hypothetical effect of variations in traffic demand and/or incident duration.

Table 1.—Typical flow rates (veh/hr)

Number of lanes in one direction	Freeway capacity (S_1)	Bottleneck capacity: One lane blocked (S_3)	Bottleneck capacity: Shoulder blocked (S_3)
2	3,700	1,300	3,000
3	5,550	2,700	4,600
4	7,400	4,300	6,300

Consider the following example:

At 8:15 a.m., a three-lane freeway with a capacity of 5,550 veh/hr carries a demand flow of 4,500 veh/hr. At this time, an accident occurs and a vehicle blocks one lane, which creates a bottleneck flow of 2,700 veh/hr. It takes 25 minutes for the incident management crew to learn of the incident and arrive at the site. While the vehicle is removed, the entire freeway is closed for 5 minutes. Once the vehicle is removed, the bottleneck flow improves to 3,500 veh/hr for 10 minutes before reaching its getaway capacity (5,550 veh/hr). Hourly volumes indicate that a decrease in the demand flow (to 2,800 veh/hr) is expected at 9 a.m.

This example uses all the variables needed to compute delay and TNF as expressed in the general equations:

- S_1—the capacity flow rate of the freeway—is 5,550 veh/hr.
- S_2—the demand flow at the time of the incident—is 4,500 veh/hr.
- S_3—the initial bottleneck flow rate—is 2,700 veh/hr, which remains in effect during the 25 minutes it took the incident management crew to learn of the incident and arrive at the site (T_1).
- S_4—the adjusted bottleneck flow rate—is 3,500 veh/hr, which lasts 10 minutes (T_3).
- S_5—the revised demand—is 2,800 veh/hr, which is expected to occur at 9 a.m., or 45 minutes (T_4) after the incident.
- The entire freeway is closed for 5 minutes (T_2).

Under simpler conditions, some of these variables do not apply and are substituted with zeros.

The data are entered in the microcomputer model, and the results are obtained (fig. 5). The total delay caused by this incident is 803 vehicle-hours, and it would take 71 minutes for the effects of the incident to dissipate.

If it took only 15 minutes for the incident management crew to learn of the incident and arrive at the site, T_1 would be changed to 15 minutes (fig. 6). Total delay then would be reduced to 572 vehicle-hours, and TNF would be reduced to 61 minutes.

Summary

This article describes analytical procedures to estimate delay, TNF, and the Q_{max} caused by freeway incidents and discusses the availability of an interactive LOTUS 1-2-3 spreadsheet for fast computations. This microcomputer tool easily can be used to estimate the impact of planned incidents (that is, lane closures during construction or maintenance operations) and the consequences of freeway incidents for immediately determining the optimum traffic control strategy.

This spreadsheet can be obtained, without charge, by mailing an IBM-formatted, 5 ¼-in floppy disk to:

Juan M. Morales
Federal Highway Administration
Traffic Safety Research Division, HSR-30
6300 Georgetown Pike
McLean, VA 22101-2296
Telephone (703) 285-2499

A METHOD FOR CALCULATING DELAY, TIME AND QUEUE FOR TRADE-OFF ANALYSES

Any Place, U.S.A.

Number of Lanes:		3
Capacity flow rate of the facility, veh/hr.....S1 =		5550
Initial demand flow rate, veh/hr.....S2 =		4500
Initial bottleneck flow rate, veh/hr.....S3 =		2700
Adjusted bottleneck flow rate, veh/hour.....S4 =		3500
Revised demand flow rate, veh/hr.....S5 =		2800
Incident duration until first change, min.....T1 =		25
Duration of total closure, min.....T2 =		5
Incident duration under adjusted flow, min.....T3 =		10
Elapsed time under initial demand, min.....T4 =		45
RESULTS: Total Delay, veh-hrs =		803.4
Time to Normal Flow (TNF), min =		71.3
Maximum extent of queue, veh =		1375
Maximum length of queue, miles =		2.60

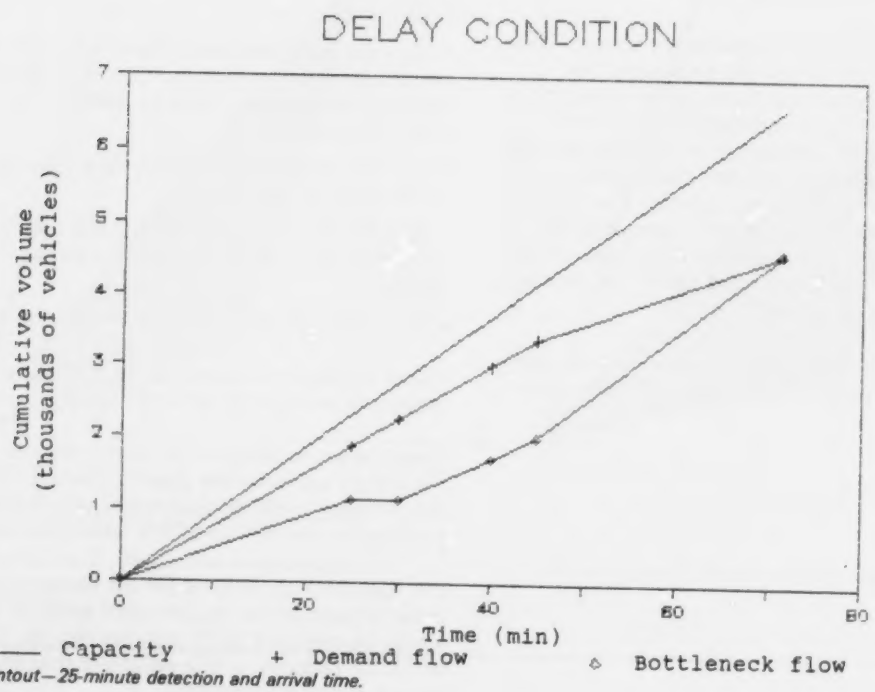


Figure 5.—Sample printout—25-minute detection and arrival time.

A METHOD FOR CALCULATING DELAY, TIME AND QUEUE FOR TRADE-OFF ANALYSES

Any Place, U.S.A.

Number of Lanes: 3

Capacity flow rate of the facility, veh/hr	S1 =	5550
Initial demand flow rate, veh/hr	S2 =	4500
Initial bottleneck flow rate, veh/hr	S3 =	2700
Adjusted bottleneck flow rate, veh/hour	S4 =	3500
Revised demand flow rate, veh/hr	S5 =	2800
Incident duration until first change, min	T1 =	15
Duration of total closure, min	T2 =	5
Incident duration under adjusted flow, min	T3 =	10
Elapsed time under initial demand, min	T4 =	45

RESULTS:

Total Delay, veh-hrs =	572.5
Time to Normal Flow (TNF), min =	60.9
Maximum extent of queue, veh =	1242
Maximum length of queue, miles =	2.35

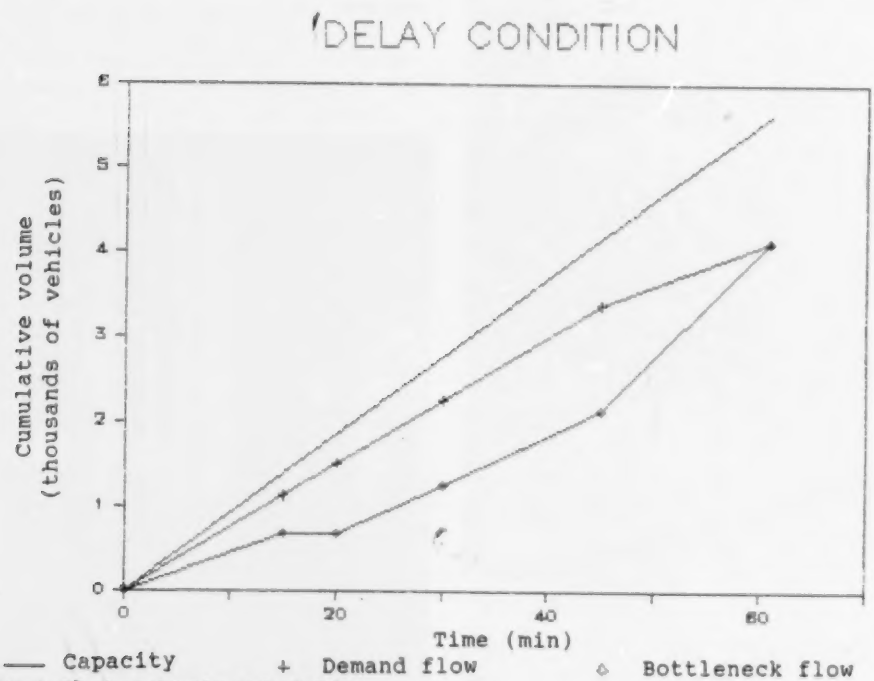


Figure 6.—Sample printout—15-minute detection and arrival time.

REFERENCES

(1) "Alternative Surveillance Concepts and Methods for Freeway Incident Management," Report Nos. FHWA-RD-77-58/63, *Federal Highway Administration,* Washington, DC, March 1978.

(2) J.A. Lindley and S.C. Tignor, "Getaway Flow Rates for Freeway Incident and Geometric Bottlenecks," *Public Roads,* vol. 43, No. 1, June 1979, pp. 1-7.

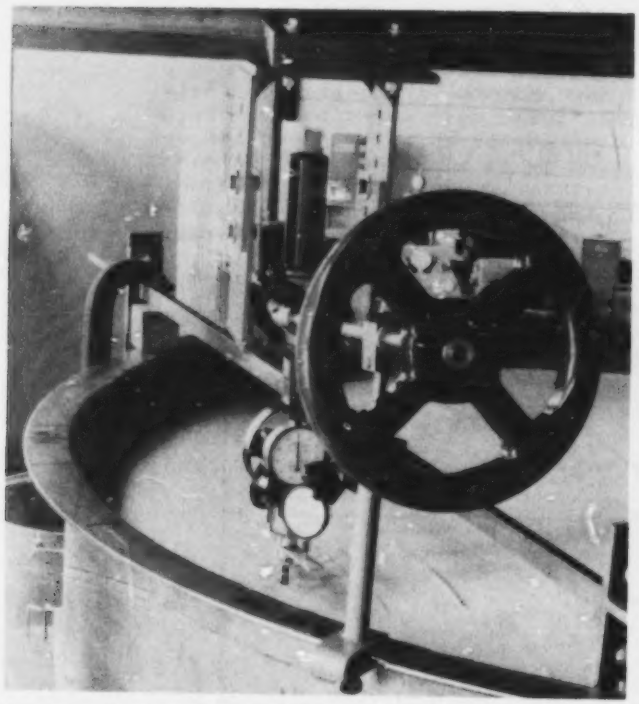
(3) J. Duke, J. Shofer, and A. May, "A Statistical Analysis of Speed-Density Hypotheses," Highway Research Record 154, *Transportation Research Board,* Washington, DC, 1967.

(4) "Highway Capacity Manual—Special Report 209," *Transportation Research Board,* Washington, DC, 1985, p. 6-7.

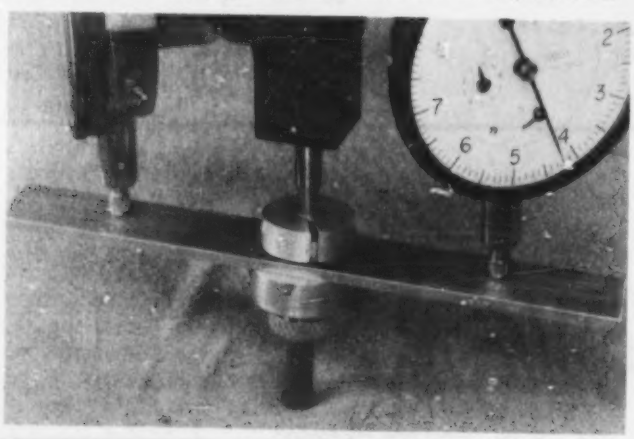
Juan M. Morales is a highway research engineer in the Traffic Safety Research Division, Office of Safety and Traffic Operations R&D, Federal Highway Administration. Since 1983 he has been working in FCP Project 1A, "Traffic and Safety Control Devices," and FCP Project 1M, "Rural Two-Lane Highways."

Soil Mechanics Laboratory and Bridge Foundation Test Facility at the Turner-Fairbank Highway Research Center

The laboratories and outdoor testing facilities at the Turner-Fairbank Highway Research Center in McLean, Virginia, enhance greatly the potential scope and quality of the Federal Highway Administration in-house research program.



Screw-actuator for applying vertical loads to a model timber pile in sand.



Closeup of load test on a model timber pile in sand.

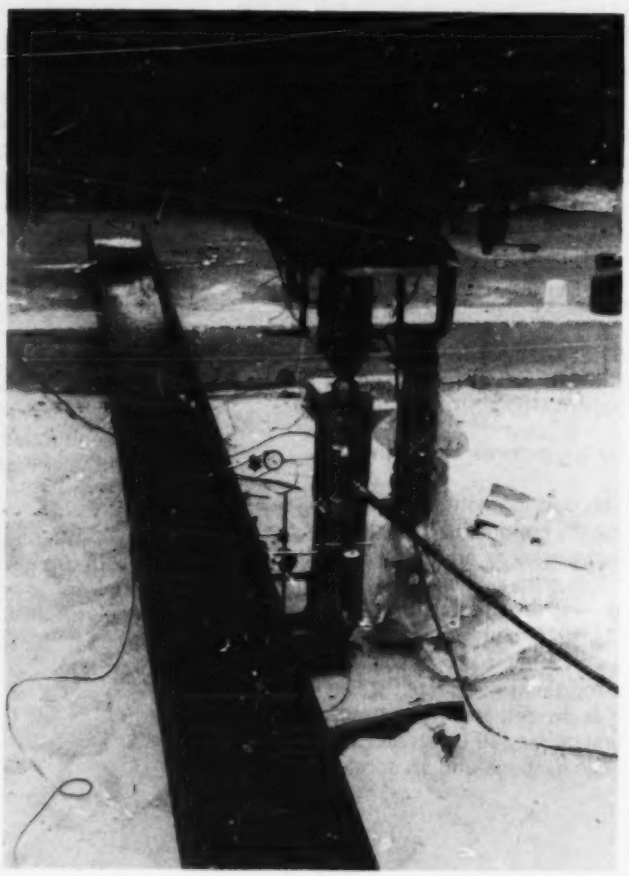
Driving one of eight fully instrumented model timber piles in sand.

The **Soil Mechanics Laboratory** is equipped to prepare soil specimens and to conduct soil mechanics tests (triaxial shear, direct shear, laboratory vane shear, incremental load, and controlled gradient consolidation) and subgrade pavement tests (California bearing ratio and Hveem stabilometer). To support staff research on small-scale piles and pile groups, the laboratory contains scaled-down pile drivers, in situ soil testing equipment, test tanks in which various foundation soils are simulated, and load test apparatus to test small-scale (1/10 to 1/100 actual size) pile groups to optimize pile foundations for highway structures.

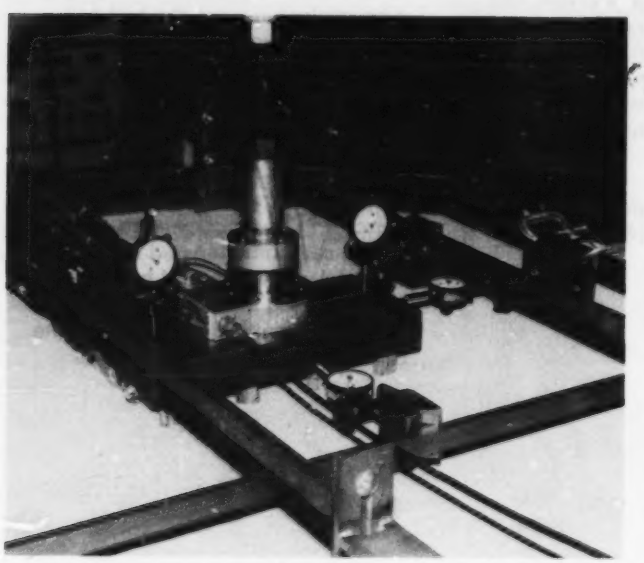
The **Bridge Foundation Test Facility** is an outdoor foundation testing facility for evaluating new design and construction concepts for spread footings and pile foundations. The test facility provides a valuable link between the small-scale testing program in the Soil Mechanics Laboratory and full-scale tests performed at actual bridge sites and other field locations. The two large test pits (20 ft x 20 ft x 20 ft [6.1 m x 6.1 m x 6.1 m]) and adjacent load test reaction systems can accommodate model sizes up to one-half scale and different soil conditions with full instrumentation and monitoring systems.

Current research in the laboratory tanks and outdoor pits involves driving and load testing model timber piles in sand. In 1987, the research in the laboratory tanks and outdoor pits will involve driving and load testing model metal piles in clay.

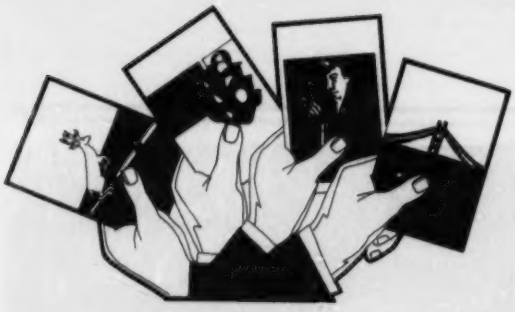
Load test on a one-quarter scale fully instrumented model timber pile in an outdoor sand test pit.



Closeup of load test on a one-quarter scale model timber pile in an outdoor sand test pit.



Load test on a fully instrumented model timber pile group in sand.



Recent Research Reports You Should Know About

The following are brief descriptions of selected reports recently published by the Federal Highway Administration, Offices of Research, Development, and Technology (RD&T). The Office of Engineering and Highway Operations Research and Development (R&D) includes the Structures Division, Pavements Division, and Materials Division. The Office of Safety and Traffic Operations R&D includes the Traffic Systems Division, Safety Design Division, and Traffic Safety Research Division. The reports are available from the source noted at the end of each description.

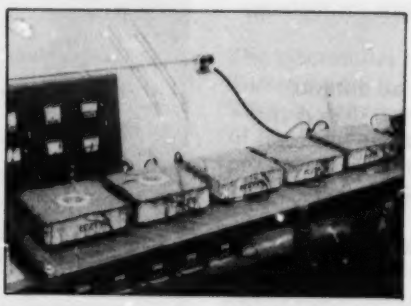
When ordering from the National Technical Information Service (NTIS), use PB number and/or the report number with the report title and address requests to:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

Electrically Conductive Polymer Concrete Overlays, Report No. FHWA/RD-84/033

by Structures Division

The development of a built-up, electrically conductive polymer concrete overlay and a premixed, electrically conductive polymer concrete mortar for use on bridge decks and other concrete members, in conjunction with cathodic protection systems, is discussed in this report. The research was divided into two phases. In the first phase, 18 commercially available resin systems and 16 conductive filler



systems were evaluated as were various parameters affecting the electrical resistivity properties of both the built-up overlay and premixed mortar systems. In the second phase, the physical and mechanical properties of the most promising overlay and premixed mortar systems were evaluated. Also, the performance characteristics of the selected overlay systems, when incorporated into active cathodic protection systems, were evaluated. The report includes recommendations regarding the further development and use of both the built-up, electrically conductive overlay and the premixed, electrically conductive mortar systems.

The report may be purchased from NTIS (PB No. 86 114873).

Evaluation of Cathodic Protection (CP) Criteria for the Rehabilitation of Bridge Decks, Report No. FHWA/RD-83/048

by Structures Division

When a bridge deck was replaced because of corrosion of the reinforcing steel from deicing salts, sections of the deck were salvaged to evaluate various cathodic protection systems. Also evaluated were the half-cell potential and constant current values obtained from the beginning of the Tafel slope on the E log I curve. The effectiveness of each criterion was monitored by electrical resistance probes (bars) that changed their electrical resistance when affected by corrosion. The probes were embedded in salt-contaminated concrete at the level of the top and bottom mat of reinforcing steel. The cathodic protection currents were applied to the concrete by cutting longitudinal

anode grooves 3/8 in (9.5 mm) wide and 0.5 in (12.7 mm) deep on 1-ft (0.3-m) center-to-center spacing. The grooves contained an electrically conductive strand of carbon filament and were backfilled with electrically conductive polymer concrete. Measurements were made to determine the current distribution when the anodes were electrically energized on a 1-ft (0.3-m) center-to-center spacing. Procedures are given in the report for obtaining an E log I curve using an oscilloscope so that the measurements are not adversely affected by turning the current on and off to obtain polarized potentials.

The report may be purchased from NTIS (PB No. 86 113701).

Ice-Melting Characteristics of Calcium Magnesium Acetate, Report No. FHWA/RD-86/005

by Materials Division

This report presents pertinent chemical and physical properties of calcium magnesium acetate (CMA). Calcium-magnesium ratios varying from 100 percent calcium acetate to 100 percent magnesium acetate were compared to determine the optimum composition of CMA for road deicing.

In a 12-month study involving wetting/drying tests with 11 ratios of calcium to magnesium and 5 pH's, it was found that CMA at pH's above 7.0 and at any calcium-magnesium ratio produced no more harm to portland cement concrete than did sodium chloride. In addition, with compositions containing magnesium at levels equal to or greater than calcium, the damage to concrete was significantly reduced.

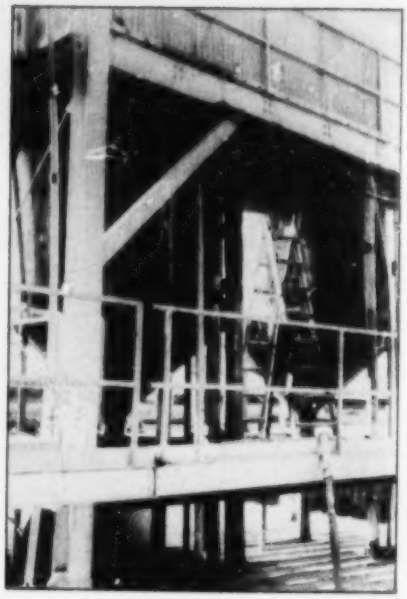
The lowest eutectic temperature (freezing point) was determined to occur with 3 mole fractions calcium to 7 mole fractions magnesium. The optimum pH for CMA was determined to be at least pH 7, with pH 9 the likely upper limit. The optimum calcium-magnesium ratio was determined to be $3Ca/7Mg \pm 1$ unit.

The report may be purchased from NTIS (PB No. 86 142742).

Preparation of High-Quality Calcium Magnesium Acetate Using a Pilot Plant Process, Report No. FHWA/RD-86/006

by Materials Division

In the research discussed in this report, a pilot plant-size drum pelletizer was used to produce over 200 lb (90 kg) of calcium magnesium acetate (CMA) from unslaked dolomitic lime and acetic acid. Data from the single-step operation are directly scalable to industrial units having 125 ton/hr (113 Mg/hr) nominal capacity.

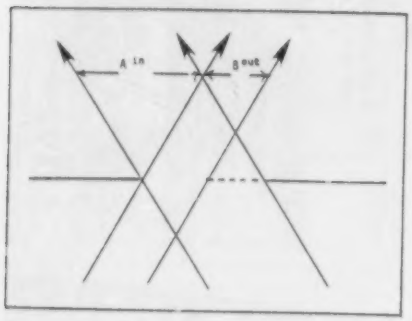


Particle-size distribution of pea-size CMA product pellets is relatively narrow. Attrition resistance is comparable to, or better than, that of commercial rock salt deicer. Product solution pH is 7.4, and at least 0.2 mols of hydration water are retained per mol of calcium acetate. The CMA produced exhibits superior ice-melting characteristics.

Capital cost is estimated at $3 million for an 80,000 ton/yr (72.6 Gg/yr) plant. At a stream factor of 0.5, total operating cost is 5.5 cents/lb (12 cents/kg) CMA beyond the acetic acid input cost.

The report may be purchased from NTIS (PB No. 86 141082).

Directional Weighting for Maximal Bandwidth Arterial Signal Optimization Programs, Volume I—Technical Report, Report No. FHWA/RD-86/020, and Volume II—Description of the Algorithm, Report No. FHWA/RD-86/022



by Traffic Systems Division

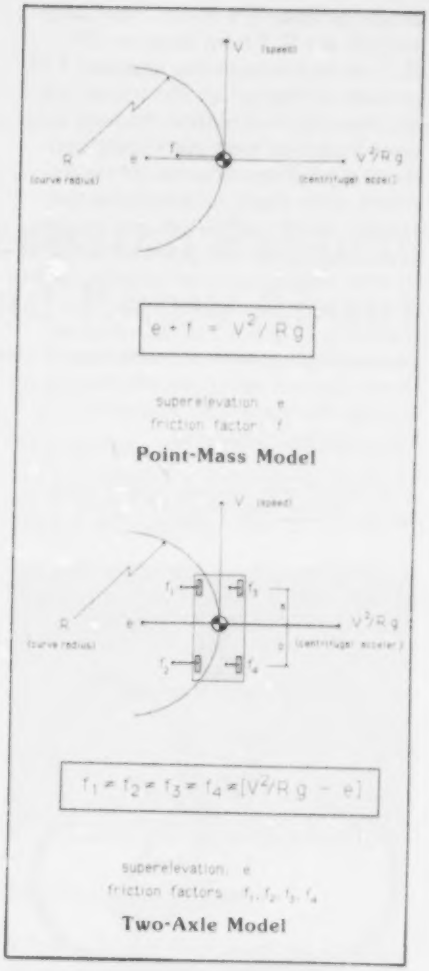
The bandwidth progression concept has been used for approximately 60 years to calculate optimal offsets in arterial signal systems. Recent studies conducted by FHWA indicated that proportioning the total two-way bandwidth in the ratio of volume distribution does not necessarily provide the lowest systemwide delay. These reports describe a study that developed an algorithm for determining the best directional weighting for arterial bandwidth optimization programs such as MAXBAND or PASSER II. This algorithm will help improve design and operation decisions, especially with heavily directional arterial street movements during peak hours.

The reports may be purchased from NTIS (PB Nos. 86 116928 and 86 116910).

Side Friction for Superelevation on Horizontal Curves, Executive Summary, Report No. FHWA/RD-86/024, Final Technical Report, Report No. FHWA/RD-86/025, and Appendixes, Report No. FHWA/RD-86/026

by Safety Design Division

These reports present the results of a study that addressed the adequacy of point-mass representations in predicting friction requirements for vehicles operating along superelevated curves. The study focused on this issue and related questions by combining computer analysis and full-scale vehicle testing. Simple-to-use models for predicting the friction factor requirements at individual wheel locations first were developed and applied to the steady-turning condition. An existing comprehensive computer model for predicting transient or nonsteady maneuvering situations also was used to analyze friction demand while maneuvering along superelevated curves. Highway tests then were performed using two passenger cars and a five-axle tractor-semitrailer to collect representative test data and assist in validating the predictions of the computer models. Finally, a sensitivity analysis was performed to illustrate the relative importance of and interactions among various vehicle parameters and highway geometrics in influencing side friction requirements.



The reports may be purchased from NTIS (PB Nos. 86 114907, 86 114915, and 86 127123).

Test and Evaluation of Eccentric Loader BCT Guardrail Terminals, Volume 1—Research Report, Report No. FHWA/RD-86/009, and Volume 2—Appendixes, Report No. FHWA/RD-86/010

by Safety Design Division

These reports discuss the test and evaluation of two W-beam guardrail terminal systems known as eccentric loader breakaway cable terminals (BCT). The two terminals, while quite similar, are characterized by a 4-ft (1.2-m) flare offset and a 1.5-ft (0.5-m) flare offset. Both designs were crash tested successfully using the four-test terminal matrix described in National Cooperative Highway Research Program Report 230.

Volume 1 contains a summary of the tests, design drawings for the terminal systems, and recommendations for the implementation of these designs.

Volume 2 contains the full-scale crash test reports and describes design concepts conceived during the project that were not evaluated by crash tests.

The reports may be purchased from NTIS (PB Nos. 86 123692 and 86 123700).

Implementation/User Items "how-to-do-it"

The following are brief descriptions of selected items that have been completed recently by State and Federal highway units in cooperation with the Office of Implementation, Offices of Research, Development, and Technology (RD&T), Federal Highway Administration. Some items by others are included when the items are of special interest to highway agencies.

Requests for items available from the RD&T Report Center should be addressed to:

Federal Highway Administration
RD&T Report Center, HRD-11
6300 Georgetown Pike
McLean, VA 22101-2296
Telephone: 703-285-2144

When ordering from the National Technical Information Service (NTIS), use PB number and/or the report number with the report title and address requests to:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

State-of-the-Practice Retroreflective Measurement Devices for Pavement Markings, Report No. FHWA-TS-84-222

by Office of Implementation

This report identifies the current use and availability of instruments for measuring the retroreflectivity of pavement marking as well as associated standards for and causes

of retroreflection from pavement markings. Tests of existing instruments were evaluated and equipment designs were compared.

The report may be purchased from NTIS (PB No. 86 165297).

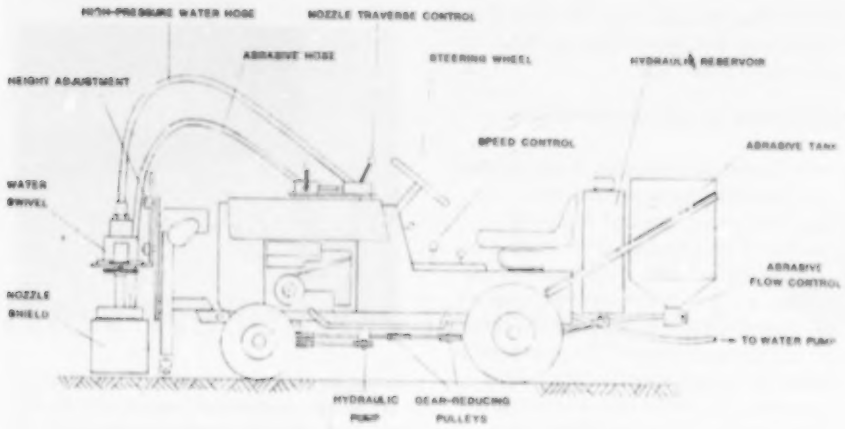
Asphalt Pavement Rutting—Western States, Report No. FHWA-TS-84-211

by Office of Implementation

A series of workshops were conducted in late 1983 to develop a set of guidelines to assist the Western Association of State Highway and Transportation Officials (WASHTO) States in preventing or reducing rutting in asphalt pavements. Representatives from most of the WASHTO States participated and provided input. It was agreed that because so many variables contributed to asphalt rutting, it is unlikely that a single cause or solution could be identified. Nevertheless, it was the consensus of the States that the highest short-term payoffs could be achieved by improving and strengthening State procedures in mixture design, materials, and construction practices. Recommendations for aggregate acceptance, paving asphalt cements, mixture design criteria, compaction control, traffic data, and information exchange were developed. In general, it was felt that rutting could be prevented or reduced if most or all of the recommendations were adopted. This report reflects the discussions at the workshops and summarizes the recommendations.

ASPHALT PAVEMENT RUTTING
WESTERN STATES

The report may be purchased from NTIS (PB No. 86 156460).



Concrete Removal With Abrasion Jet, Report No. FHWA-TS-85-221

by Office of Implementation

An abrasive waterjet system was designed and built to demonstrate the system's ability to remove bridge deck concrete. The removal system consisted of two rotating abrasive nozzles mounted on the front of a garden tractor. A hydraulic system was used to move the nozzles across the front of the tractor. The abrasive tank was mounted on the rear of the tractor. The pump system was a trailer-mounted 120 hp (89.5 kW) triplex pump capable of delivering 9 gal/min (34 L/min) at a maximum pressure of 20,000 psi (138 MPa).

The field testing phase of this project was not as complete as planned, and a few system components did not perform as well as desired. The rate of removal by this rotating nozzle abrasive system is relatively low in comparison with conventional concrete removal methods.

The report may be purchased from NTIS (PB No. 86 164704).

Recessed Reflective Markers Feasibility Study, Report No. FHWA-TS-86-207

by Office of Implementation

Conventional glass bead traffic stripes generally provide poor delineation under wet-night conditions. Many States, especially in the north, have complemented the stripes with reflectors positioned adjacent to or in line with the normal striping. Reflectors, placed in recessed grooves, have shown low susceptibility to damage from snowplows.

Manually installing reflectors after the pavement has been placed requires cutting the pavement to provide the groove. Approximately 45 percent of the installation cost is for the diamond cutting blades required to cut the pavement. This report documents the results of an FHWA study that tested and evaluated candidate systems for forming the grooves during paving operations. Recommendations are included for field testing and additional research needs.

The report may be purchased from NTIS (PB No. 86 164696).

Longitudinal Edge Drains in Rigid Pavement Systems, Report No. FHWA-TS-86-208

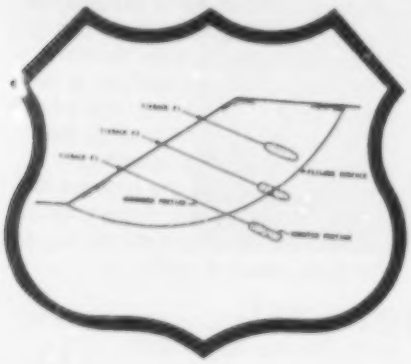
by Office of Implementation

This report documents the findings of a four-State study of longitudinal edge drain systems used in rigid pavements. Design philosophies and criteria, construction practices, and field performance comparisons are discussed, as well as where edge drains may not be advisable.

Trench drains and drainable asphalt concrete layers were found to be cost-effective in terms of their original cost and in their ability to remove water. Performance comparisons with 7-year-old pavements without drainage provisions indicate that edge drains can extend pavement life. Maintenance of the edge drain system contributed to pavement performance.

The report may be purchased from NTIS (PB No. 86 168317).

PCSTABL4 Users Manual, Report No. FHWA-TS-85-229



by Office of Implementation

This report describes the operation of the two-dimensional, limiting equilibrium, slope stability microcomputer program PCSTABL4. A short review of the program's capabilities and hardware and software requirements are presented, as are instructions for operating the program on a microcomputer. Three example problems are included to familiarize the user with the program.

The report and program may be purchased from the School of Civil Engineering, Purdue University, West Lafayette, Indiana 47907.

Tolerable Movement Criteria for Highway Bridges, Report No. FHWA-TS-85-228

by Office of Implementation

This report summarizes a comprehensive research program on the tolerable movement of highway bridges that was begun in 1978 and completed in 1983. This research included a state-of-the-art assessment of tolerable bridge movements based on a literature review; an appraisal of existing design specifications and practice; the collection and analysis of field data on foundation movements, structural damage, and the tolerance to movements for 314 bridges in the United States and Canada; and an appraisal of the reliability of the methods currently used for settlement prediction. Also included were a series of analytical studies to evaluate the effect of different magnitudes and rates of differential movement on the potential level of distress produced in a wide variety of steel and concrete bridge structures of different span lengths and stiffnesses and the development of a methodology for the design of

bridges and their foundations that embodies a rational set of criteria for tolerable bridge movements.

Limited copies of the report are available from the RD&T Report Center

New Research in Progress

The following new research studies reported by FHWA's Offices of Research, Development, and Technology are sponsored in whole or in part with Federal highway funds. For further details on a particular study, please note the kind of study at the end of each description and contact the following: Staff and administrative contract research—*Public Roads* magazine; Highway Planning and Research (HP&R)—performing State highway or transportation department; National Cooperative Highway Research Program (NCHRP)—Program Director, National Cooperative Highway Research Program, Transportation Research Board, 2101 Constitution Avenue, NW., Washington, DC 20418.

FCP Category 1—Highway Design and Operation for Safety

FCP Project 1A: Traffic and Safety Control Devices

Title: Stop Signs Used With Flashing Traffic Signals. (FCP No. 31A2204)
Objective: Install blank-out stop signs at two locations in Orlando, Florida. Choose two similar signal locations without blank-out stop signs to serve as a control. Collect and analyze accident record data at these four locations.
Performing Organization: Development Assistance Corporation, Washington, DC 20001
Expected Completion Date: March 1987
Estimated Cost: $24,000 (FHWA Administrative Contract)

Title: Manual on Uniform Traffic Control Devices (MUTCD) Research Data Base. (FCP No. 21A3174)
Objective: Operate, maintain, and increase the computer data base developed on research related to traffic control devices.
Performing Organization: Federal Highway Administration, McLean, VA 22101
Expected Completion Date: January 1988
Estimated Cost: $8,000 (FHWA Staff Research)

FCP Project 1K: Accident and Countermeasure Analysis

Title: Application of Bayesian Statistics to Highway Safety Analysis. (FCP No. 21K3055)
Objective: Demonstrate the applicability of the empirical Bayesian statistics to highway safety analysis.
Performing Organization: Federal Highway Administration, McLean, VA 22101
Expected Completion Date: June 1987
Estimated Cost: $7,000 (FHWA Staff Research)

FCP Category 4—Pavement Design, Construction, and Management

FCP Project 4A: Pavement Management Strategies

Title: Pavement Materials and Design. (FCP No. 24A1011)
Objective: Determine the structural properties of pavement materials for pavement management research. Develop materials test and pavement analysis procedures by evaluating indirect tensile tests; analyzing data obtained from previous staff work (deflection profiles of the east and west pits at four different temperatures and three different loads); developing a pavement performance data base; developing mechanistic damage models for inverse solutions; and determining the effects of mix design and compaction on permanent deformation.
Performing Organization: Federal Highway Administration, McLean, VA 22101
Expected Completion Date: September 1987
Estimated Cost: $35,000 (FHWA Staff Research)

Title: Development of a Pavement Design and Rehabilitation Guide for Puerto Rico. (FCP No. 44A1502)
Objective: Collect and analyze data. Select test sections, collect historical data, and then conduct field and laboratory tests. Change the current pavement design guide based on data analysis. Adapt rehabilitation techniques to local conditions, and conduct a workshop.
Performing Organization: University of Puerto Rico, Mayaguez, PR 11111
Funding Agency: Puerto Rico Department of Transportation and Public Works
Expected Completion Date: March 1988
Estimated Cost: $76,185 (HP&R)

Title: Microcomputer Analysis for Project Level Pavement Management Systems for Rigid and Composite Pavements. (FCP No. 44A2332)
Objective: Develop a decision support system for project level pavement management to enable engineers to make the optimum selection of pavement strategies for individual highway segments. Develop a life-cycle cost analysis procedure for rigid and composite pavements to enable engineers to specify measures to rank alternatives and set criteria to manipulate the ranks.
Performing Organization: University of Maryland, College Park, MD 20742
Funding Agency: Maryland State Highway Administration
Expected Completion Date: March 1987
Estimated Cost: $50,000 (HP&R)

Title: Monitoring of Pavement Rehabilitation Techniques. (FCP No. 44A2392)
Objective: Monitor pavement rehabilitation techniques used in the State of Maryland, and examine other rehabilitation techniques used nationwide. Identify and recommend for use specific rehabilitation techniques that are most cost-effective for a particular kind of pavement distress.
Performing Organization: Maryland State Highway Administration, Baltimore, MD 21211
Expected Completion Date: March 1991
Estimated Cost: $17,300 (HP&R)

Title: Pavement Deflection Evaluation. (FCP No. 44A3132)
Objective: Establish, maintain, and collect statewide deflection data base (rigid, flexible, composite, and other pavement sections). Use data for model development, evaluation, verification, and modification of the design and for construction quality control of materials.
Performing Organization: University of Kentucky, Lexington, KY 40506
Funding Agency: Kentucky Transportation Cabinet
Expected Completion Date: December 1990
Estimated Cost: $25,000 (HP&R)

Title: Laboratory and Field Evaluations and Correlations of Properties of Pavement Components. (FCP No. 44A3462)
Objective: Correlate back-calculated material properties from field deflection tests. Evaluate deflection models, and study how the values change with time. Verify and modify design practices based on study results, which will give values of layer material properties. Develop acceptance tests based on moduli.
Performing Organization: University of Kentucky, Lexington, KY 40506
Funding Agency: Kentucky Transportation Cabinet
Expected Completion Date: April 1992
Estimated Cost: $20,215 (HP&R)

FCP Project 4B: Design and Rehabilitation of Rigid Pavements

Title: Portland Cement Concrete Pavement Performance and Rehabilitation. (FCP No. 44B1353)
Objective: Model selected existing urban portland cement concrete pavements in Washington State to define failure modes, estimate deterioration rates, and develop optimum rehabilitation alternatives and timing. Perform extensive in situ sampling, instrumentation, nondestructive testing, and analysis.
Performing Organization: Washington State Department of Transportation, Olympia, WA 98504
Expected Completion Date: December 1987
Estimated Cost: $200,000 (HP&R)

FCP Project 4C: Design and Rehabilitation of Flexible Pavements

Title: Fine Aggregate Shape and Surface Texture. (FCP No. 44C2124)
Objective: Evaluate the influence of variation in fine aggregate shape and surface texture on the properties of asphalt mixtures. Evaluate the ability of a series of test methods to predict the effect of these fine aggregate properties on the characteristics of the mix. Correlate these test results with standard Marshall mix design results and field performance.
Performing Organization: Western Technologies, Inc., Phoenix, AZ 85036
Funding Agency: Arizona Department of Transportation
Expected Completion Date: May 1987
Estimated Cost: $89,000 (HP&R)

Title: Evaluation of Bituminous Pavement With Polypropylene Fiber. (FCP No. 44C6265)
Objective: Evaluate the performance of a bituminous overlay of a pavement containing 0.3 percent polypropylene fiber.
Performing Organization: Mississippi State Highway Department, Jackson, MS 39215
Expected Completion Date: December 1990
Estimated Cost: $7,400 (HP&R)

☆U.S. Government Printing Office: 1986—491-825/40004

FCP Category 5—Structural Design and Hydraulics

FCP Project 5A: Bridge Loading and Design Criteria

Title: Post Delineator Mechanical Fatigue Behavior. (FCP No. 45A2242)
Objective: Review the literature related to the fatigue of flexible delineation posts, visit manufacturers, investigate long-term fatigue properties, establish performance specifications, and develop an automated performance testing system.
Performing Organization: Ohio University, Athens, OH 45701
Funding Agency: Ohio Department of Transportation
Expected Completion Date: January 1988
Estimated Cost: $81,415 (HP&R)

Title: Use of Welded Mesh in Reinforced Concrete Bridge Decks. (FCP No. 45A3272)
Objective: Develop design guidelines for using welded steel mesh in reinforced concrete bridge decks.
Performing Organization: University of Maryland, College Park, MD 20742
Funding Agency: Maryland State Highway Administration
Expected Completion Date: April 1989
Estimated Cost: $116,383 (HP&R)

Title: Distribution of Post-Tensioning Forces Prior to Grouting Tendons. (FCP No. 45A4092)
Objective: Review current facts and practices and test specimens to define the relationship and simplify the design of post-tension applications. Determine whether simplification of design calculations is justified.
Performing Organization: University of Texas at Austin, Austin, TX 78712
Funding Agency: Texas State Department of Highways and Public Transportation
Expected Completion Date: August 1987
Estimated Cost: $36,000 (HP&R)

Title: Grid Analysis of Wide, Short-Span, Continuous Curved Box Girders Using Curved Member Properties. (FCP No. 45A4122)
Objective: Develop an analysis method that enables a designer to analyze wide, short-span, continuous curved box girders by synthesizing the bridge as an assemblage of beams and slabs. Develop a computer program to perform grid analysis while incorporating curved member properties.
Performing Organization: Mississippi State University, State College, MS 39762
Funding Agency: Mississippi State Highway Department
Expected Completion Date: October 1987
Estimated Cost: $31,200 (HP&R)

Title: Evaluation of Cast-in-Place Concrete Inserts. (FCP No. 45A4132)
Objective: Perform structural tests on two common kinds and four brands of cast-in-place concrete inserts. Develop comprehensive guidelines for designers to follow when inserts are required.
Performing Organization: California Department of Transportation, Sacramento, CA 95809
Expected Completion Date: April 1989
Estimated Cost: $17,000 (HP&R)

FCP Project 5K: Bridge Rehabilitation Technology

Title: Development of Ultrasonic Techniques to Establish Flaw Size. (FCP No. 45K1252)
Objective: Study thoroughly some of the most promising techniques (such as "time-of-flight," tandem transducers, and flaw area-transducer area-misorientation angle) that are feasible for shop and field use. Fabricate test pieces with flaws whose size, type, and orientation will be determined by x ray from different directions or by sectioning.
Performing Organization: California Department of Transportation, Sacramento, CA 95809
Expected Completion Date: December 1988
Estimated Cost: $5,080 (HP&R)

FCP Project 5Z: Implementation of Structural and Hydraulics R&D

Title: Drilled Shaft Manual. (FCP No. 35ZP248)
Objective: Revise and update a previous implementation package, FHWA-IP-77-21, to reflect research and information available since 1977. Add chapters on construction techniques and specifications. Develop a workshop package and a slide-tape package that will summarize the advantages of drilled shaft foundations and encourage their consideration for a variety of foundation needs.
Performing Organization: Association of Drilled Shaft Contractors, Garland, TX 75041
Expected Completion Date: January 1988
Estimated Cost: $60,000 (FHWA Administrative Contract)

FCP Category 0—Other New Studies

Title: Conversion of Travel and Facilities Data Processing From Mainframe to Microcomputer. (FCP No. 40PN046)
Objective: Research, identify, purchase, and install microcomputer hardware and software for collecting, assembling, manipulating, and printing data in standard report form.
Performing Organization: Arizona Department of Transportation, Phoenix, AZ 85007
Expected Completion Date: March 1987
Estimated Cost: $25,000 (HP&R)

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COVER: An ongoing project at West Virginia University is evaluating a major natural brine deicing program. The Connecticut high-pressure sprayer was used in Phase I of the research, which is discussed in the first article.

U.S. Department of Transportation
Elizabeth Hanford Dole, *Secretary*

Federal Highway Administration
R.A. Barnhart, *Administrator*

U.S. Department of Transportation
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Washington, DC 20590

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The Secretary of Transportation has determined that the publication of this periodical is necessary in the transaction of the public business required by law of this Department.

Contents of this publication may be reprinted. Mention of source is requested.

The Use of Oil and Gas Field Brines as Highway Deicing Agents[1]

by

Ronald W. Eck and William A. Sack

Introduction

Because of environmental problems and tight operating budgets, highway agencies are seeking ways to minimize the use of the traditional deicing chemicals—sodium and calcium chlorides. A variety of approaches has been proposed (*1-3*)[2], including using naturally occurring salt brines—a waste product of oil and gas production. As a liquid, brine has the advantages of being fast-acting, and it does not blow or bounce off of the roadway.

Using natural brine for deicing could solve several problems simultaneously. The oil and gas industry could dispose of an unwanted byproduct, and highway agencies could acquire a deicing material at minimal cost. Furthermore, the natural brine would be applied at controlled rates rather than be unlawfully discharged directly into the ground or into surface waters (resulting in contamination) as is frequently done now in some areas. Using the brine for deicing would eliminate the need to import thousands of tons of rock salt into a State or region each year and would reduce the amount of salt in the environment.

[1]This article is adapted from "Determining the Feasibility of West Virginia Oil and Gas Field Brines as Highway Deicing Agents," Phase I, final report, West Virginia Department of Highways, Research Project 68, *Department of Civil Engineering, West Virginia University*, Morgantown, WV, January 1984.

[2]Italic numbers in parentheses identify references on page 81.

An ongoing project at West Virginia University is evaluating a major natural brine deicing program by researching the following issues:

- Brine quality from the major producing formations (including both the major salts and the minor and trace constituents).
- Comparison of brines with commercial deicing agents relative to melting, skid resistance, and refreezing of roadway surfaces.
- Corrosion of metals and concrete and bituminous pavement deterioration characteristics.
- Quantity of brine available for highway deicing in a given geographical area.
- Estimates of transportation and storage costs.

This article discusses laboratory and field studies addressing the first three issues listed above; the remaining issues are beyond the scope of this article.

Laboratory Evaluation

Brine characteristics

Forty-nine samples of natural brine were collected over a 17-month period in Phase I of the project. The oil and gas industry was extremely supportive of the work—five companies provided brine samples and/or quantities of brine. Samples were obtained from 13 different counties and 12 separate West Virginia oil and gas fields. Brines were collected from 8 different geological formations, which included more than 12 different oil and gas zones. The depths of wells from which samples were taken ranged from 1,980 to 11,380 ft (603 to 3 469 m). In all cases, the brines were collected from above-ground steel storage tanks located at the wellhead. Some of the wells were sampled repeatedly during the project to observe possible changes in brine quality with time.

To analyze the composition of the 49 brines collected, 20 different kinds of tests were performed, although not all of the tests were carried out for each sample because of time and resource constraints. The constituents determined were divided into four main groups: General parameters—total dissolved solids (TDS's), conductivity, density, pH, and acidity; major constituents—chloride, sodium, calcium, magnesium, and potassium; minor constituents—iron, sulfate, barium, ammonia, and total organic carbon (TOC); and trace constituents—cadmium, chromium, arsenic, lead, and zinc.

The range and mean value for each test parameter are given in table 1. Although mean values are presented in each case, the mean concentration is not very meaningful for parameters such as barium where variations in barium levels between brines from different formations are very large. Table 1 also presents a range of values reported for brines in West Virginia, Pennsylvania, and Ohio. (*4-6*) The range given is not meant to be comprehensive, but represents a sampling of brines with TDS's greater than 80 000 mg/L (0.66 lb/gal) that were judged to be typical of brines produced in the three States.

General parameters and major constituents—The TDS's of the samples collected range from 90 420 to 323 700 mg/L (0.75 to 2.70 lb/gal), with a mean value of 218 600 mg/L (1.82 lb/gal). Brine strength generally increased with depth. The mean calcium concentration was over 31 000 mg/L (0.26 lb/gal). This is significant because the presence of calcium salts allows the use of deicing agents at lower temperatures than is feasible with sodium salts alone.

Minor and trace constituents—Iron ranged from 28 to 750 mg/L (0.00023 to 0.0062 lb/gal), with a mean value of 276 mg/L (0.0023 lb/gal). Sulfate levels, which varied from less than 5 to 547 mg/L (mean of 163 mg/L) (0.000041 to 0.0045 lb/gal [mean of 0.0014 lb/gal]), are of interest with respect to attack of concrete. Sulfate levels of 150 mg/L (0.0012 lb/gal) or less would result in negligible attack on concrete, levels of 150 to 1 500 mg/L (0.0012 to 0.012 lb/gal) would result in a positive degree of attack, and levels above 1 500 mg/L (0.012 lb/gal) would result in a severe degree of attack. (*7*) Also to be considered is that brine applied to the roadway would be diluted by snow or ice almost immediately and would run off as melting occurred. It is conceivable that a heavy application rate of brine containing high sulfate levels could result in sulfate attack if there was limited snow and ice meltwater for dilution. However, under most field situations, the sulfate levels in West Virginia brines would not be expected to contribute significantly to concrete deterioration. The materials testing work, reported later in this article, supports this conclusion.

Barium levels varied widely among the brine samples, ranging from 1.3 to 2 500 mg/L (0.000011 to 0.021 lb/gal). Barium levels greater than 100 mg/L (0.00083 lb/gal) occurred in 22 of the 48 samples analyzed for barium. However, almost all of the high barium samples were taken from two particular geological formations in one field.

Ammonia and TOC levels also were examined for a limited number of samples. The level of ammonia ranged from 11 to 386 mg/L (0.000091 to 0.0032 lb/gal), while TOC varied from 6 to 45 mg/L (0.000050 to 0.00037 lb/gal). These levels are not likely to pose environmental problems when using brine for deicing because of the relatively small quantities of brine used in comparison with the quantity of meltwater runoff.

Table 1.—Project brine concentration compared with reported values

Constituent	Range—Project Brines	Mean—Project Brines	Reported Range (4-6) WV, OH, PA
TDS (mg/L)	90,420-323,700	218,600	80,000-373,000
Conductivity (micromhos/cm)	200,000-605,000	413,800	140,000-598,000
Density (lb/gal)	9.191-10.129	9.774	8.985-10.235
pH	2.72-6.14	NA	4.4-6.5
Acidity (mg/L)	80-227	144	2-560
Cl (mg/L)	57,510-192,420	128,600	52,500-190,840
Na (mg/L)	29,130-82,240	52,740	37,150-75,000
Ca (mg/L)	5,470-57,900	31,310	8,790-49,000
Mg (mg/L)	645-4,950	3,200	1,900-10,000
K (mg/L)	30-3,310	590	122-8,200
Fe (mg/L)	28-750	276	2-560
SO_4 (mg/L)	<5-547	163	0-1,100
Ba (mg/L)	1.3-2,500	545	0-1,150
NH_3-N (mg/L)	11-386	51	7-450
TOC (mg/L)	6-45	29	NA
Cd (mg/L)	<.01-1.627	.365	<.1-6.0
Cr (mg/L)	<.06	<.06	<.1-.7
As (mg/L)	.138-.457	.263	NA
Pb (mg/L)	1.583-6.100	3.360	<.1-6.0
Zn (mg/L)	.212-1.739	.619	0-13

1 mg/L = 8.345 × 10^{-6} lb/gal
1 micromhos/cm = 0.398 micromhos/in
1 lb/gal = 119 826 mg/L

The values for the five trace constituents analyzed—cadmium, chromium, arsenic, lead, and zinc—are generally in the ranges reported for the three States. Each of these trace constituents, except zinc, has a maximum limit based on toxicity under the Resource Conservation and Recovery Act (RCRA) of 1976. Barium also is limited by RCRA. It is important to note that production brines are excluded from regulation under RCRA and are compared with RCRA-regulated wastes simply to gain a perspective on the trace constituent levels. RCRA limits are as follows: arsenic-5 mg/L (0.000041 lb/gal); barium-100 mg/L (0.00083 lb/gal); cadmium-1 mg/L (0.0000083 lb/gal); chromium-5 mg/L (0.000041 lb/gal); and lead-5 mg/L (0.000041 lb/gal). Comparing RCRA limits with values obtained for the 49 project brines in table 1 suggests that barium is the only constituent of concern. The elevated cadmium and lead values were found in only 2 of the 49 brines and were only slightly higher than the RCRA allowable levels. As noted earlier, most of the samples with high barium levels originated from one oil and gas field. Brines from formations with unacceptably high trace element levels must either be pretreated to reduce the element before highway application or be rejected.

All brine sources most likely would be analyzed for a variety of major and trace elements before being approved for application. The frequency of subsequent testing of a given source would depend on the requirements of the particular State or agencies involved. In this project, the brines sampled from a given source were relatively constant in quality over the 17-month period. Hence, re-testing certain key parameters from the source every 2 years would be adequate. Costs of brine analysis would have to be included as part of the cost of the brine application program. However, the oil and gas companies would likely bear a substantial portion of the brine analysis costs.

Brine variability

One of the objectives of the brine sampling program was to evaluate variability in quality from different formations and zones as well as changes in brine quality over the 17-month sampling period for a given formation. The change in brine quality between locations for a given formation or zone also was evaluated.

Nine different sample groups, based on the number of formations, zones, counties, or wells from which the samples were taken, were made to evaluate variability. For each group, an average percent coefficient of variation (standard deviation divided by the mean) was determined for eight sample parameters—TDS, chloride, sodium, calcium, magnesium, arsenic, lead, and zinc. As would be expected, the lowest variation was observed for samples taken from single wells. The single-well samples had an average percent coefficient of variation of 6.6 for the eight sample parameters. Samples taken from single wells over a 13-month period showed no trend in increasing or decreasing concentration with time. Brine variability increased (for the same formations) as samples were taken from greater distances and from a greater number of zones. For example, the largest formation group variability (24.8 percent coefficient of variation) occurred for a group that contained samples from six counties and three zones.

As would be expected, the largest variation in brine quality was between different formations. For example, brines sampled from a deep lying formation were almost twice as strong as those from more shallow formations.

Comparison of constituents in dry deicing agents and brines

It would be expected that the dry agents—sodium and calcium chlorides—used for deicing or road stabilization also would contain a variety of minor and trace constituents. Seven dry agents were analyzed for six minor and trace substances as shown in table 2. The sodium and calcium chloride samples randomly were collected over a 2-year period from the West Virginia Department of Highways, the West Virginia University physical plant, and the City of Morgantown. Also shown in table 2 are results adapted from an analysis of dry sodium chloride used in Pennsylvania. (*4*) The brine group values presented are average values for each constituent.

Examination of the data shows that the dry agents as well as the brines contain a variety of trace constituents. The brines are generally higher in iron, zinc, and barium, while the dry agents are higher in chromium and cadmium. The dry calcium chloride samples also had elevated lead levels when compared with the brines.

Table 2.—Comparison of constituents in dry deicing agents and brines (mg/kg TDS)

Agent	Constituent					
	Chromium	Lead	Iron	Cadmium	Zinc	Barium
			Dry Salts			
NaCl-WVDOH[1]-1982	2.4	5.8	9.1	8.3	.7	–
NaCl-Mgtn[2]-1982	1.9	5.4	10.6	8.9	.6	–
NaCl-Mgtn-1983	–	–	–	10.4	–	132
NaCl-WVDOH-1983	–	–	–	9.1	–	96
NaCl-WVU-PP[3]-1982	2.7	6.2	17.3	6.1	.3	–
$CaCl_2$-WVDOH-1982	6.2	53.9	24.4	16.6	2.0	–
$CaCl_2$-WVU-PP-1982	8.5	46.0	27.6	18.4	2.3	–
NaCl-Penn	.7	8.8	12.3	1.7	.8	.1
			Brines			
Group 1A	<.2	14.6	1350	1.1	3.4	4838
Group 2A	<.3	17.3	1122	2.5	3.0	454
Group 2C	<.2	18.7	783	4.8	3.2	21.7
Group 2D	<.3	12.2	315	<.05	2.9	50.8
Group 3B	<.3	14.4	631	2.5	2.0	65.5

[1]West Virginia Department of Highways.
[2]Morgantown.
[3]West Virginia University physical plant.
1 mg/kg = 8.345 × 10^{-6} lb/gal

Surface degradation

Because brines contain a larger number of constituents than do traditional deicing agents, the well-known detrimental effects of sodium and calcium chlorides on highway materials cannot be assumed to apply to natural brines. The effects of brines on two paving materials—bituminous concrete and portland cement concrete—were assessed in the laboratory. These materials were subjected to distilled water, a 100 000-mg/L (0.83-lb/gal) TDS solution of sodium and calcium chloride (50:1 ratio of sodium to calcium), and a 100 000-mg/L (0.83-lb/gal) TDS solution of natural brine diluted with distilled water.

A bituminous concrete mixture representative of those used in pavement surfaces in West Virginia was used to prepare 50 standard Marshall specimens. Specimens were divided into the three treatment groups noted above, with each group having three subgroups (exposure to 10, 50, and 100 freeze-thaw cycles), plus a control group for a total of 10 groups. Each group consisted of five replicate specimens to provide statistical reproducibility.

Figure 1 shows that the specimens exposed to distilled water experienced a reduction in Marshall stability, while all but one of the salt solutions showed higher stabilities than the control value. Results of t-tests performed on the data indicated that there were no statistically significant changes in Marshall stability between specimens subjected to rock salt and those subjected to natural brine. In addition, results suggested that saline solutions will not significantly change the Marshall stability of bituminous concrete. These results are consistent with previous research. (*8*)

A surface degradation test to evaluate concrete performance was conducted on specimens prepared from a portland cement mix typical of that used for highway pavements in West Virginia. The surface degradation test specimens were divided into five groups. For each group, five specimens were fabricated. Two different procedures (freeze-thaw and wet-dry) were selected to simulate the field conditions existing when deicing chemicals are applied. The wet-dry test was conducted at constant rather than varying temperatures. ASTM Method C 672, "Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Salts," was followed. (*9*)

Figure 2 shows the mean effect of each of the three solutions on the scaling resistance of portland cement concrete subjected to freezing and thawing. Specimens covered with distilled water showed no change in surface condition; the 0- to 5-scale visual rating of the surface remained at 0 (no scaling) for all five specimens during the entire 100-cycle study period.

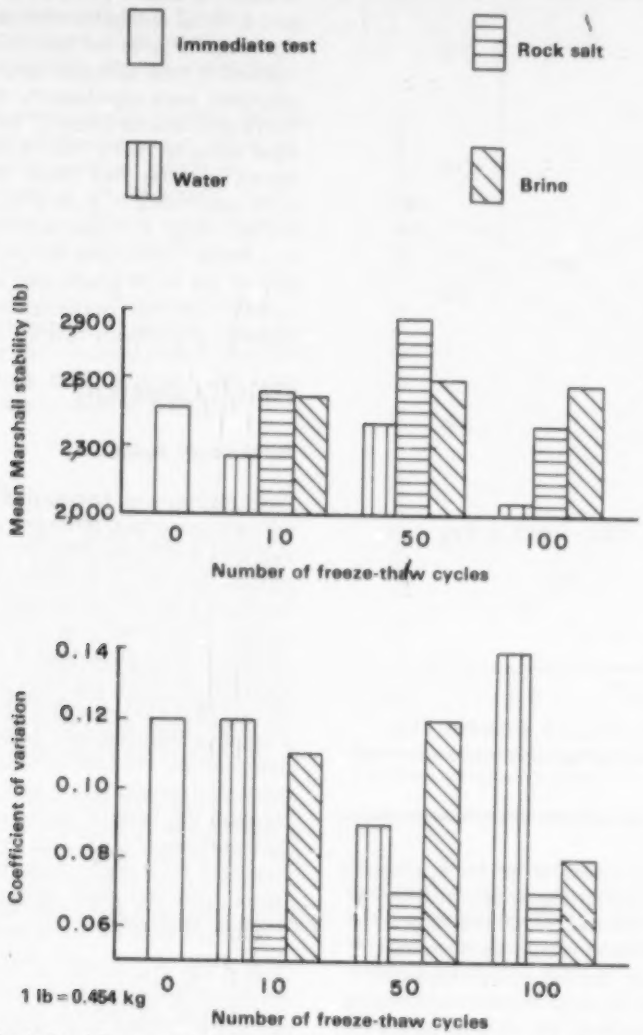


Figure 1.—Marshall stability test results for bituminous concrete specimens subjected to freeze-thaw cycles of water, rock salt solution, and natural brine.

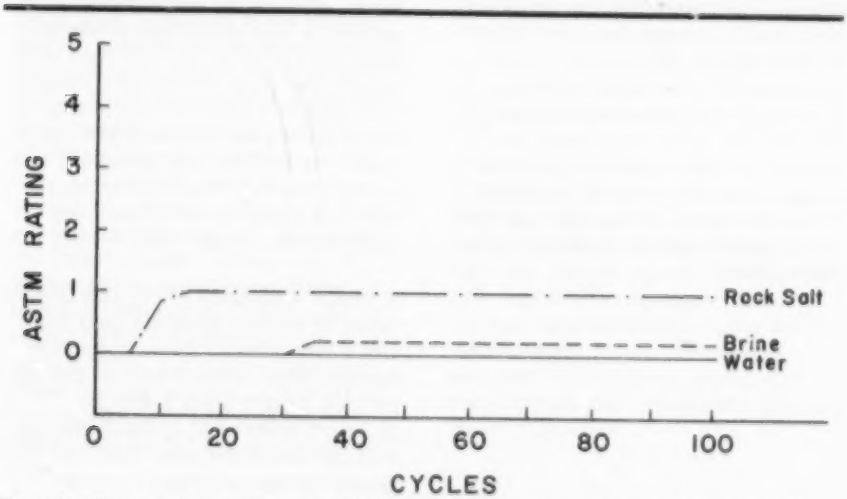


Figure 2.—Effect of deicer solutions on surface scaling of concrete specimens subjected to freeze-thaw cycles. Values shown are means of five specimens.

Concrete specimens subjected to the sodium and calcium chloride solution showed the earliest scaling. Specimens subjected to natural brine solution scaled later and showed less scaling than did those subjected to the sodium and calcium chloride solution. Thus, natural brine appears to be no more detrimental to portland cement concrete pavement surfaces than are traditional deicing agents.

Specimen groups that underwent wet-dry cycles were rated using the same scheme as for the freeze-thaw tests. Neither the specimens subjected to brine nor those exposed to the sodium and calcium chloride solution showed any scaling through the 100 cycles.

Steel corrosion

A wet-dry immersion test in which metal specimens were alternately immersed and removed from salt solutions was used as an accelerated corrosion test. Corrosion was measured by weight loss. Two kinds of steel were tested—A-36 steel was chosen to represent the steel used in highway construction and SAE-1010 steel was selected to represent that used in automobile bodies. The experimental procedure essentially followed ASTM Method G 31, "Laboratory Immersion Corrosion Testing of Metals." (*10*) Each group of specimens was photographed as it was removed from the test solution, and the surface condition of each specimen was visually evaluated. Each specimen then was cleaned and weighed.

Weight loss data for the automobile body steel specimens are shown in figure 3. As expected, the curves become asymptotic. Specimens immersed in the sodium and calcium chloride solution lost slightly more weight than those immersed in natural brine (4 percent difference after 100 cycles).

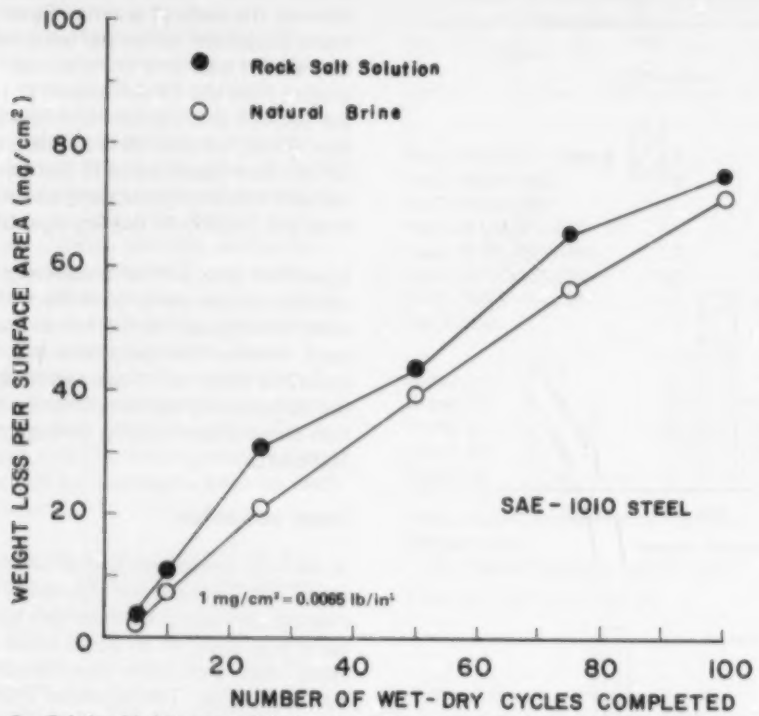


Figure 3.—Relationship between weight loss per surface area and number of cycles completed for SAE-1010 steel specimens submerged in deicing solutions.

A least-squares regression analysis indicated that there were no differences in corrosion between rock salt and natural brine; however, some qualitative differences were observed. The surfaces of the specimens immersed in brine remained relatively smooth, whereas the surfaces of the specimens immersed in the sodium and calcium chloride solution were noticeably rougher with high and low anode areas. After 100 cycles, the bottom edges of the specimens immersed in the sodium and calcium chloride solution were severely corroded and had lost about 2 mm (0.08 in) from their original length. Similarly, the other three edges had lost their original shape, indicating that the weight loss was more rapid around the edges. Weight loss was uniformly distributed over specimens immersed in natural brine.

Careful examination of the specimens revealed no pitting in any of the groups, even after 100 wet-dry cycles. Pitting would be even less with liquid deicing agents because there are no large crystals to become trapped against the surface of the metal.

Weight loss results for the structural steel specimens are shown in figure 4. Through the 25th cycle, specimens immersed in both solutions had essentially identical weight losses. Beyond this point, specimens immersed in natural brine lost more weight than did those immersed in the sodium and calcium chloride solution (a difference of 22 percent after 100 cycles).

A least-squares regression analysis and a visual evaluation indicated that the weight losses for specimens immersed in rock salt and natural brine solutions were significantly different. Surface characteristics of the A-36 steel were different from those obtained with the SAE steel. Structural steel specimens in both solutions exhibited rough surfaces with high and low areas. There was no pitting in any of the A-36 specimens after 100 cycles; however, some specimens showed a tendency toward cratering.

Field Evaluation

Applicator systems

Field testing was conducted for four winters using two different applicator systems and three different spray modes. Initially, a portable high-pressure hydrodynamic applicator system consisting of a 1,500-gal (5.68-m³) fiberglass tank, a distributor bar with 28 small diameter nozzles, a 25-hp (18.6-kW) gasoline engine, and a positive displacement pump and designed by the Connecticut Department of Transportation was acquired through the Federal Highway Administration. (*11-13*) The system was mounted on a dump-body truck obtained from the West Virginia Department of Highways.

During the first winter of Phase I, corrosion products from the steel spray bar tended to plug the 0.08-in (2.03-mm) diameter nozzle openings, reducing sprayer effectiveness. In addition, discussions with maintenance personnel from a number of highway agencies indicated that the high initial cost of the spray-bar system, coupled with potential maintenance problems, might reduce its attractiveness. As a result, the system was converted to gravity flow by removing the nozzles from the spray bar and then used to complete the Phase I field testing.

A Phase II research effort was undertaken to design, fabricate, and field test a low-pressure brine applicator system. Main components of this applicator system are a 2,450-gal (9.27-m³) steel tank, a distributor bar that can accommodate from four to seven nozzles, a sprayer control

system, and a centrifugal pump. The system is mounted on a tandem dump-body truck. The truck's hydraulic system powers the pump.

For each spraying run, careful records were kept of the amount of brine applied and the weather conditions. To monitor melting effectiveness, roadway surface conditions were photographed and visually assessed at periodic intervals after the brine was applied. A limited amount of pavement skid resistance testing was done using the British pendulum tester. On several runs, brine and rock salt were applied side-by-side to compare results.

Results

Eight field runs using high-pressure application were made on the West Virginia University campus during the first winter of Phase I testing. Four runs with gravity flow were made on a 2.8-mi (4.5-km) section of State highway during the following winter. To date, 17 runs have been made using the low-pressure spray system.

Table 3 summarizes the field runs for the first three winters in which testing took place. In general, 500 lb (227 kg) of TDS's were applied per two-lane mile of highway—the application rate used by the West Virginia Department of Highways on Interstate and other limited-access facilities. The application rates during the first winter (1981-1982), indicated in table 3, were higher than desired for several reasons: The researchers' inexperience in operating snow removal and ice control equipment, restrictive roadway geometrics that seriously limited truck speeds, and unplowed test roadways requiring repeat applications to induce melting. These drawbacks were overcome during succeeding winters when brine was applied (by experienced personnel in the West Virginia Department of Highways) to a section of State highway with higher speeds and higher traffic volumes. As shown in table 3, brine application rates under these conditions were comparable with typical rock salt application rates—500 lb (227 kg) per two-lane mile.

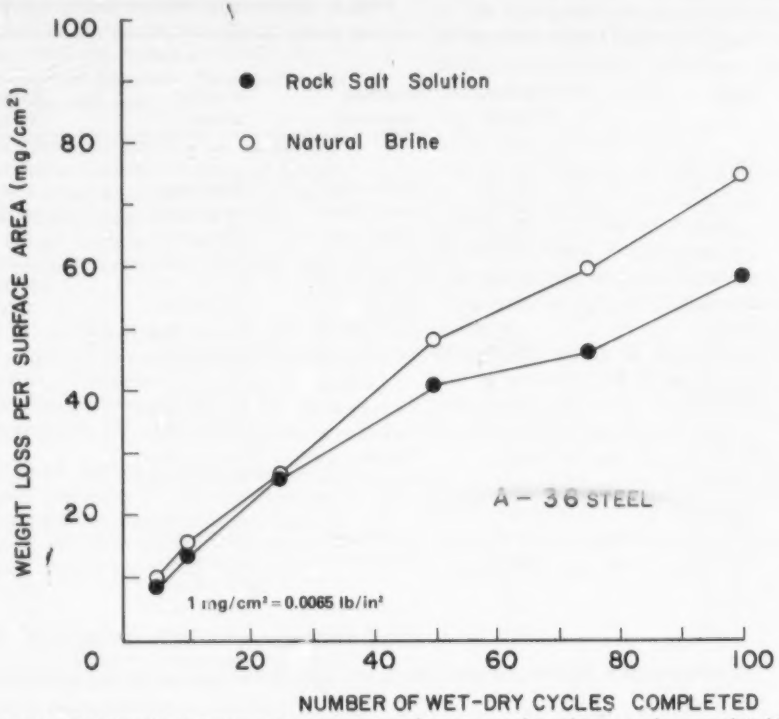


Figure 4.—Relationship between weight loss per surface area and number of cycles completed for A-36 steel specimens submerged in deicing solutions.

Overall, brine performance was similar to that of rock salt. Brines were effective in melting snow and ice and achieving bare pavement within a relatively short time. In cases where heavy snowfall continued after brine application, the roads again would become covered with snow, requiring a second brine application. However, this also was true for roads treated with rock salt.

Summary and Recommendations

Many natural brines from the Central Appalachian Region (including West Virginia, Ohio, Pennsylvania, and New York) are suitable for use as highway deicing agents. Brines from this region have relatively high calcium concentrations—an asset in deicing applications. Of the minor and trace constituents analyzed in these brines, barium was the only element of concern.

Major variations in brine quality result from differences in formation and zone. Brines from different formations have significantly different concentrations of major and trace constituents. Also, brine strength tends to increase with depth. Over a period of 13 months, there was no change in brine concentration from a given formation. It is recommended that brines continue to be monitored to determine any long-term changes in composition.

The constituents of the natural brines examined were compared with those of conventional chloride chemicals. The brines generally were higher in iron, zinc, and barium, while the conventional chemicals were higher in chromium and cadmium. Dry calcium chloride samples had elevated lead levels when compared with the brines.

Table 3.—Summary of field test results for three winters

Date	Temp. (°F)	Roadway conditions	Mode of delivery	Speed (mi/h)	Lb TDS / Two-lane mile	Comments
1981–1982						
12/17/81	28–30	Loose snow	Hi-pressure	–	697	Produced bare pavement
1/9/82	14–17	Loose snow	Hi-pressure	4–10	1,480	Better melting than NaCl[1]
1/16/82	28–31	Loose snow	Hi-pressure	6	1,693	Bare pavement quickly
1/25/82	16–22	Packed snow	Hi-pressure	12–15	355	Bare pavement achieved
2/11/82	17–19	Packed snow	Hi-pressure	11	1,422	Slow melting due to cold
2/13/82	21–25	Loose snow	Hi-pressure	4–10	1,750	Excellent meltoff
3/3/82	25	Packed snow	Gravity flow	12	534	Produced bare pavement
4/6/82	26–30	Packed snow	Gravity flow	7	506	Good meltoff
1982–1983						
1/12/83	21	Packed snow	Gravity flow	26	534	Same results as NaCl
1/15/83	17	Packed snow	Gravity flow	25	506	Melted ice pack
2/6/83	26	Packed snow	Gravity flow	23	182	Slush after 15 min
2/11/83	17	Packed snow	Gravity flow	23	659	Results identical to NaCl
1984–1985						
1/10/85	26–28	Loose snow	Lo-pressure	18	441	Rapid meltoff
1/10/85	29–30	Packed snow	Lo-pressure	15	1,227	Immediate meltoff
1/11/85	25–27	–	Lo-pressure	–	–	–
1/17/85	24	Loose snow	Lo-pressure	17	623	Produced bare pavement
1/17/85	26	Packed snow	Lo-pressure	17	656	Same results as NaCl

[1]All comparisons to NaCl in this table refer to a sodium chloride application rate of approximately 500 lb (227 kg) per two-lane mile.

°F = 1.8°C + 32
1 mi/h = 1.6 km/h
1 lb = 0.454 kg

In general, the effects of natural brines on bituminous concrete pavements appear to be no different than the effects of traditional rock salt deicing agents. The use of natural brines resulted in less portland cement concrete surface deterioration than did the use of conventional chloride deicers during 100 freeze-thaw cycles. Although some discoloration of the concrete occurred because of iron in the brines, the problem is not expected to be significant under actual field conditions.

No general statement could be made about the relative effects of natural brine and rock salt on steel corrosion because the effects depend upon the chemical compositions of the steels and brine. In this study, specimens of automobile body steel demonstrated less corrosion in natural brine than in a sodium and calcium chloride solution. However, specimens of structural steel yielded opposite results.

Chloride deicers create serious problems on reinforced concrete bridges because the expansion behavior of the corrosion products disrupts the concrete cover. Reinforcing steels usually have a higher carbon content than do those tested in this study, thus the results are not directly transferable, and corrosion tests with a reinforcing-type steel in concrete should be conducted. A number of studies have been performed to evaluate methods for protecting reinforced concrete from the adverse effects of deicing salts. (*14–17*) Review of these studies provides insight about testing procedures that could be applied to evaluating the effects of natural brines on reinforced concrete.

Field testing conducted during three winters shows that West Virginia oil and gas field brines are effective deicing agents for a variety of weather and pavement conditions using either gravity or high-pressure application. Visible melting began to occur almost immediately after the brine was applied, and bare pavement was achieved rapidly on low-volume roadways, even at temperatures of 15 °F (−9.4 °C). The brines were effective at low temperatures probably because the brines used contained significant amounts of calcium as well as of sodium salts.

REFERENCES

(1) "Minimizing Deicing Chemical Use," National Cooperative Highway Research Program Synthesis of Highway Practice 24, *Transportation Research Board*, Washington, DC, 1974.

(2) S.A. Dunn and R.M. Schenk, "Alternate Highway Deicing Chemicals," Report No. FHWA-RD-79-108, *Federal Highway Administration*, Washington, DC, March 1980.

(3) L.D. Minsk, "Optimizing Deicing Chemical Application Rates," CRREL Report 82-18, *U.S. Army Cold Regions Research and Engineering Laboratory*, Hanover, NH, August 1982.

(4) B.A. Waite, S.C. Blauvelt, and J.L. Moody, "Oil and Gas Well Pollution Abatement Project ME No. 81495," *Moody and Associates, Inc.*, Meadville, PA, 1983.

(5) H.A. Hoskins, "Interpretations of Salt Water Analyses," *Appalachian Geological Survey Bulletin*, vol. 1, 1949.

(6) C.W. Poth, "The Occurrence of Brines in Western Pennsylvania," Bulletin M47, *Pennsylvania Topographic and Geologic Survey*, Harrisburg, PA, 1962.

(7) J.S. Pierce, "Use of Fly-Ash in Combating Sulfate Attack in Concrete," The Challenge of Change—Sixth International Ash Utilization Symposium Proceedings, *U.S. Department of Energy, Morgantown Energy Technology Center*, Morgantown, WV, July 1982, pp. 208-231.

(8) B.F. Kallas, "Performance of Asphalt Pavements Subjected to Deicing Salts," Highway Research Record 24, *Highway Research Board*, Washington, DC, 1963, pp. 49-61.

(9) "Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals," 1985\Annual Book of ASTM Standards, Vol. 04.02, Designation C 672-84, *American Society for Testing and Materials*, Philadelphia, PA, 1985, pp. 426-428.

(10) "Standard Practice for Laboratory Immersion Corrosion Testing of Metals," 1985 Annual Book of ASTM Standards Vol. 03.02, Designation G 31-72, *American Society for Testing and Materials*, Philadelphia, PA, 1985, pp. 176-185.

(11) M.A. Pickett and J.F. Carney, "Portable Hydrodynamic Brine Roadway Deicer System," Transportation Research Record 833, *Transportation Research Board*, Washington, DC, 1982, pp. 30-32.

(12) M.M. Kasinskas, "Evaluation of the Use of Salt Brine for Deicing Purposes," Transportation Research Board Special Report 185, *Transportation Research Board*, Washington, DC, 1979, pp. 275-281.

(13) "Proceedings of the High-Pressure Salt Brine System Conference (Connecticut)," Report No. FHWA-TS-81-202, *Federal Highway Administration*, Washington, DC, 1981.

(14) J.N. Hall and S.P. LaHue, "Effect of Salt on Reinforced Concrete Highway Bridges and Pavements," Transportation Research Board Special Report 115, *Transportation Research Board*, Washington, DC, 1970, pp. 115-122.

(15) R.E. Hay, "The Bridge Deck Problem—An Analysis of Potential Solutions," *Public Roads*, vol. 39, No. 4, March 1976, pp. 142-147.

(16) D.W. Pfeifer and M.J. Scali, "Concrete Sealers for Protection of Bridge Structures," National Cooperative Highway Research Program Report 244, *Transportation Research Board*, Washington, DC, December 1981.

(17) J.M. Sayward, "Salt Action on Concrete," Special Report 84-25, *U.S. Army Cold Regions Research and Engineering Laboratory*, Hanover, NH, August 1984.

Ronald W. Eck is a professor of civil engineering at West Virginia University. He has been principal investigator on several West Virginia Department of Highways/FHWA joint-sponsored research studies including winter maintenance, truck escape ramps, rail-highway grade crossings, and high-speed signalized intersections. Dr. Eck is active in the technical committees of the Transportation Research Board, Institute of Transportation Engineers, and American Society of Civil Engineers.

William A. Sack is a professor of civil engineering at West Virginia University and leader of the Civil Engineering Department's Environmental/Water Resources Group. For the past 22 years, Dr. Sack has been teaching and conducting research on industrial and municipal waste treatment and reuse.

Road Humps for the Control of Vehicular Speeds and Traffic Flow

by
Burton W. Stephens

Introduction

Road humps, sometimes referred to as undulations or speed humps, are protuberances constructed in the roadway to reduce vehicular speed. They have a unique set of design specifications that distinguish them from the more conventional road bump. Road humps, an arc approximately 12 ft (3.7 m) long and 3 to 4 in (76.2 to 101.6 mm) high, have been designed for use on residential streets that have speed limits of 25 mi/h (40 km/h) or less. In contrast, a road bump typically is an arc between 0.5 and 3.0 ft (0.15 and 0.9 m) long and 2 to 6 in (50.8 to 152.4 mm) high and is used in parking lots, on private roads, and on some residential streets. Figure 1 shows the contrast between the two road protuberances.

Another distinction between road humps and bumps is the difference in how vehicles respond to them. In general, for road humps, as speeds increase, the vertical forces to the vehicle and thus occupant discomfort increase. The opposite is true for road bumps; peak vertical accelerations and associated discomfort of vehicle occupants are great at relatively low vehicular speeds, but vertical forces and associated discomfort diminish with increasing speeds.

This article discusses the purpose and development of road humps, the effectiveness of road humps relevant to safety issues, signing and marking requirements, the benefits and problems of road humps, and other considerations. The article concludes with an assessment by city engineers, planners, and local highway administrators of the feasibility of establishing regulations and legislation on the road hump as a traffic control device.

Development of Design Specifications for Road Humps

To accomplish the three major purposes of road humps—increase the safety of residential streets, improve the environmental quality of residential neighborhoods, and improve traffic flow throughout residential areas—humps must be designed carefully because there are many possible variations in their construction that can influence vehicles traversing them. Thus, functional design requirements must be specified.

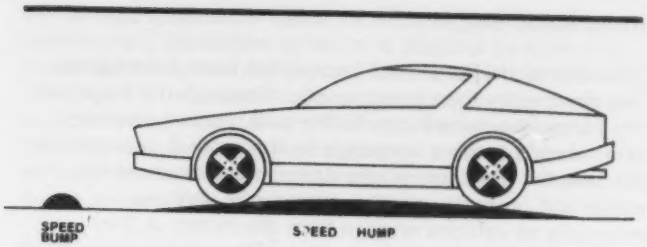


Figure 1.--Schematic representation of road hump and speed bump.

The four basic requirements of a road hump configuration are as follows:

- Increasing vehicular speed in the vicinity of road humps should be countered progressively by increasing occupant discomfort.
- Speed reductions should be maintained *throughout* the roadway section bounded by humps, not only in the vicinity of the humps.
- Speed reductions in the vicinity of humps should be gradual, facilitated by the use of road signs and markings.
- Speed reductions in the vicinity of humps should be long lasting and not merely the result of novelty or driver uncertainty.

Initial evaluations of the feasibility and effectiveness of using road humps for speed control involved test track studies that measured peak vertical vehicle acceleration and associated occupant discomfort. An important assumption underlying such data is that when discomfort reaches a threshold value, a driver will slow the vehicle. Several reseachers have used a 7-point discomfort scale to predict hump crossing speed. For a 12-ft (3.7-m) long and 4-in (101.6-mm) high hump, test track discomfort data predicted on-road vehicle speeds over the hump in the range of 14 to 21 mi/h (22.5 to 33.8 km/h). (*1*)[1] In subsequent on-road tests at nine British locations, the overall average speed at the road hump was slightly lower (11.1 mi/h [17.8 km/h]). The 85th percentile speed was 14.2 mi/h (22.9 km/h), while the overall average speed on the road segment bounded by humps was 22.2 mi/h (35.7 km/h).

Similar results were obtained in Australia (*2*) and Sweden. (*3*) Finnish research (*4*) indicates vehicle occupant discomfort levels far less than those reported by other researchers. Moderate levels of occupant discomfort were reported for only one of the five vehicles used in the Finnish tests, although operators of heavy-duty vehicles reported intolerable levels of discomfort.

Disparate results of this kind suggest that different vehicles react differently to humps, perceptions of discomfort vary among cultures, and/or the underlying attitude scales were being used differently by different researchers.

Best-fit analyses of discomfort and the peak vertical acceleration of vehicles passing over humps yield good-fit linear relationships. (*1, 4*) Assuming that a midpoint discomfort value is a threshold for speed control at the road hump, peak vertical accelerations of about 0.69 g (22 ft/s² [6.8 m/s²]) will induce the typical driver to reduce speed. For passenger vehicles with soft suspension systems, motorists will drive over the road hump at approximately 25 mi/h (40 km/h); for passenger vehicles with harder suspension systems or over-inflated tires, speeds are expected to be somewhat less. For heavy vehicles without cargo, peak vertical accelerations would be quite high, thereby inducing even slower speeds.

Physical Characteristics of Road Humps

Road hump parameters that have been varied empirically in test programs are hump length, height, and shape and the distance between humps. Ideally these parameters could be varied to design hump configurations for a prescribed traffic speed and to minimize speed variations.

Road hump length

A hump that is longer than the wheelbase of a vehicle transfers an upward force to the vehicle at low speeds, imparting a low amplitude and a simple vertical acceleration waveform to the vehicle, its occupants, and its cargo. As speed and the wheelbase-hump length difference increase, the amplitude and waveform complexity also increase, increasing occupant discomfort and the potential for damaged cargo.

Figure 2 illustrates the amplitudes and waveform complexities of vertical accelerations transferred to vehicle occupants. (*4*) The figure shows three vehicle conditions—an empty passenger vehicle, with acceleration measurements taken at the driver's seat; an empty air suspension bus, with measurements taken at the driver's seat; and the same bus with measurements taken at the back seat. As shown, the amplitude of the acceleration measures increases with increases in speed over a road hump 4 in (101.6 mm) high and 12 ft (3.7 m) long. For the passenger vehicle, the vertical acceleration is in a comfortable-to-tolerable range for all speeds. For the air suspension bus, only speeds below 20 mi/h (32 km/h) are tolerable.

Figure 3 plots the relationship between road hump length and peak vertical acceleration for a Mini Clubman Estate passenger vehicle traversing experimental 4-in (101.6-mm) high road humps at 15 to 24 mi/h (24 to 39 km/h). Although data for vertical accelerations at higher speeds are not available for all conditions and extrapolation is risky, it is clear that hump lengths of less than 12 ft (3.7 m) will cause many operators (because the Mini Clubman Estate car is representative of the class of lightweight, soft-suspension vehicles) to drive at less than 20 mi/h (32 km/h). On the other hand, humps much longer than 12 ft (3.7 m) will not cause occupants of many vehicles great discomfort but would lead to increased road hump crossing speeds for large vehicles and those with stiff suspensions.

[1]Italic numbers in parentheses identify references on page 90.

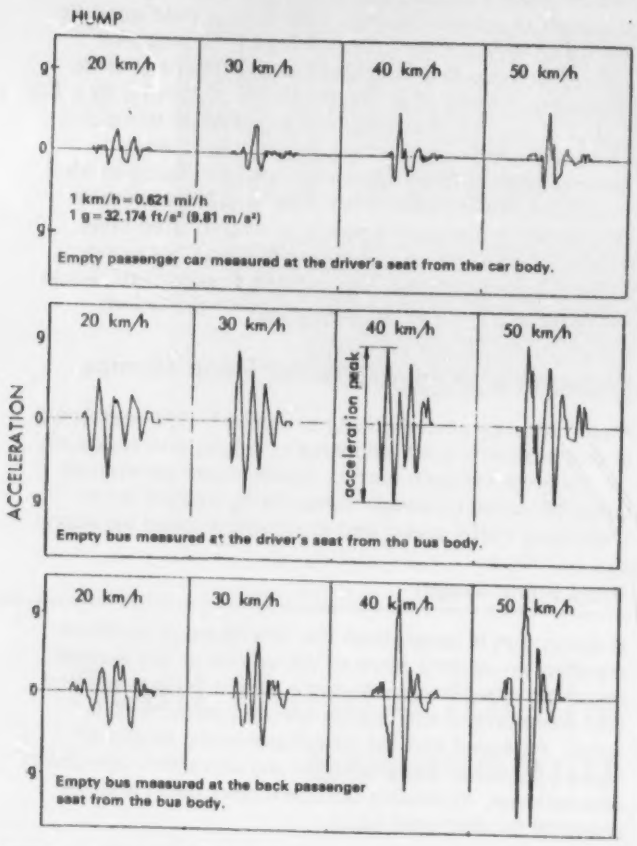

HUMP
20 km/h
30 km/h
40 km/h
50 km/h
g
0
g
1 km/h = 0.621 mi/h
1 g = 32.174 ft/s² (9.81 m/s²)
Empty passenger car measured at the driver's seat from the car body.
ACCELERATION
acceleration peak
Empty bus measured at the driver's seat from the bus body.
Empty bus measured at the back passenger seat from the bus body.

Figure 2.—Examples of peak vertical acceleration recordings as vehicles traverse a 12-ft (3.7-m) long and 4-in (101.6-mm) high road hump. (4)

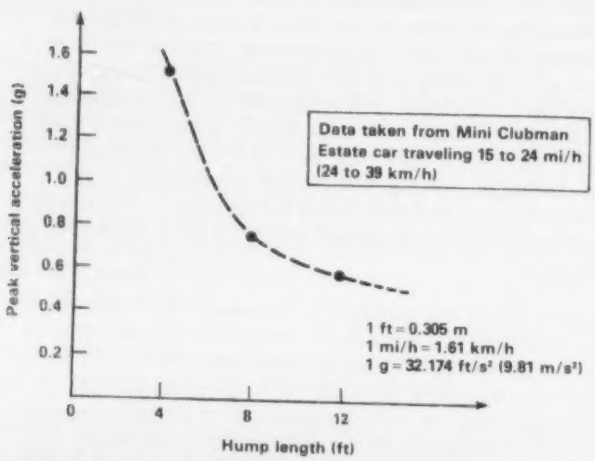


Figure 3.—Average peak vertical acceleration recorded for three hump lengths.

Road hump height

The optimal height of road humps has been investigated less thoroughly than hump length. Although the height of the hump also contributes to the peak vertical acceleration value, it is more important to the ground clearance of the vehicle. High humps can damage vehicle undercarriages and promote roadway scarring by vehicles, especially as vehicles emerge from the hump. A 3-in (76.2-mm) high hump may be optimal for lightweight, soft-suspension vehicles operating at 25 mi/h (40 km/h). Furthermore, the lower hump will scrape fewer low-riding vehicles.

In one experiment with a 12-ft (3.7-m) long hump that was 3 in (76.2 mm) high, passenger vehicle on-hump speeds were 4 mi/h (6.4 km/h) higher than speeds on 4-in (101.6-mm) high humps. (*1*) Higher on-hump speeds also lead to higher speeds between humps.

Road hump shape

As with the height of the road hump, the optimal shape has not been evaluated thoroughly. Although hump shape can modify the complexity of the vertical acceleration waveform, it probably has little impact on occupant discomfort because most of the higher frequency waveform components are negated by the vehicle characteristics or physical makeup of the occupants. Two designs used are humps with a single circular section and those with a parabolic section with a flared ramp at the entry side of the hump. (*5*) Other variations have been proposed to make the transition onto the hump smoother—for example, reversing parabolic curves at the ends of the hump. As discussed earlier, it is likely that complex waveforms are not resolved by the driver in selecting a desired speed over the road hump. The analyses of such complex shapes likely would require computer simulation tests to determine whether the peak amplitudes of the vertical acceleration patterns are modified significantly. On-road driver discomfort measurements also would be necessary. Finally, the cost-effectiveness of strict construction standards would have to be addressed.

Road hump spacing

The distance between road humps—the linear separation of individual humps—also can influence the vertical acceleration waveform. For separations of more than a few feet, there is no interaction between the vertical acceleration waveforms of the individual road humps. However, large separations lead to increased speeds between the humps. As previously mentioned, a basic requirement of road hump configurations is that constant vehicular speeds be maintained *throughout* the entire roadway section bounded by humps, including on-hump speeds.

All on-road tests show speed variations at and between road humps, the extent of which is affected by both the hump geometry and the spacing between humps. If road humps are constructed to ensure a spot speed reduction, a single hump may suffice. However, because humps generally are used to reduce speed on an entire block or series of blocks within a residential or business district, hump spacing is a critical design parameter.

Field data from the United Kingdom and Corio, Australia, show an empirical relationship between road hump spacing and speeds midway between humps. (*6*) The equation that approximately fits these data is as follows:

$$H_S = 0.50\ (2.59\ (V_{85})^2 - 656).$$

Where,

H_S = the optimal spacing of road humps (ft).
V_{85} = the desired 85th percentile speed between road humps for $V_{85} > 22.5$ mi/h.

Effectiveness of Road Humps

Overall speed effectiveness of road humps

Table 1 summarizes the effectiveness in terms of speed reduction of various road hump configurations without regard to specific configuration characteristics. As can be seen, speeds are reduced significantly at the road humps and between road humps at most studied locations. The speeds shown in table 1 are 85th percentile speeds, which ideally should converge with the speed limit on the streets where road humps have been placed.

Stability of road hump effectiveness

Figure 4 illustrates the effects over time of road humps. Although nearly all drivers are expected to be affected immediately by the humps, bringing the 85th percentile speeds to the speed limit, the faster drivers will be affected more gradually. Unlike most traffic control signs, the road hump is continuously reinforcing; that is, there is a penalty every time the driver traverses the hump at an excessive speed. Signs, however, merely inform drivers or provide the legal basis for a penalty and provide reinforcement only when an enforcement authority is present.

Two studies on road hump installations indicate that there is no regression of speeds to the pre-hump speed conditions. The effectiveness of road humps in Brea, California, was tested using speed data collected before hump construction, immediately after construction, and 3 months and 7 months after construction. (*7*) Consistency of overall speeds at reduced levels was found for all three "after" data collection periods. The fastest vehicle speed also was recorded for each of the four periods; the fastest speed occurred toward the middle of the block immediately after the road humps were installed. However, in subsequent testing periods, the overall speeds of the fastest vehicles were reduced by approximately 5 mi/h (8 km/h) compared with the "before" testing period. This is either due to a moderating influence of the humps on the fastest vehicle speeds or else operators of these vehicles chose other routes.

Table 1.—Comparison of before and after speeds at 18 locations—85th percentile speeds

Location	At-hump speed			Between-hump speed		
	Before	After	Difference	Before	After	Difference
	Miles per hour			*Miles per hour*		
Light Street (AUS)	40.4	13.0	27.4	43.5	28.0	15.5
Peacock Avenue (AUS)	32.9	18.0	14.9	33.6	25.5	8.1
Armytage Street (AUS)	30.4	16.2	14.2	32.9	26.1	6.8
Cuddesdon Way (UK)	39.0	13.5	25.5	39.0	23.0	16.0
Motum Road (UK)	30.1	12.9	17.2	30.1	25.0	5.1
Palace Road (UK)	32.1	16.3	15.8	32.1	21.9	10.2
Abbotsbury Road (UK)	39.8	14.2	25.6	39.8	27.2	12.6
Barlanark Road (UK)	35.7	15.4	20.3	35.7	21.9	13.8
College Walk (UK)	31.1	14.0	17.1	31.1	21.1	10.0
Esplande (UK)	19.0	13.0	6.0	19.0	16.3	2.7
Albron Street (UK)	30.3	14.0	16.3	30.3	20.9	9.4
Kelly Road (USA)	43.0	19.0	24.0	43.0	32.0	11.0
Silas Avenue (USA)	38.0	24.0	14.0	38.0	34.0	4.0
Silas Avenue (USA)	38.0	23.0	15.0	38.0	27.0	11.0
Cindy Avenue (USA)	27.0	21.0	6.0	27.0	23.0	4.0
46th Street (USA)	—	—	—	36.0	26.0	10.0
Lockstead Avenue (USA)	37.0	26.0	11.0	—	—	—
La Canada Drive (USA)	36.0	21.6	14.4	32.0	23.4	8.6

1 mi/h = 1.61 km/h

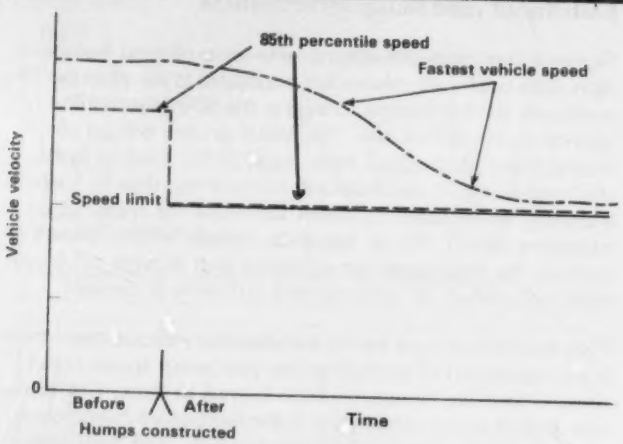


Figure 4.—Ideal temporal profile of 85th percentile and fastest vehicle speeds at site of speed zone controlled by road humps.

A study of residential streets in Corio, Australia, also provides information on effectiveness stability. (*6*) Figure 5 shows the speed distributions at humps and midway between humps. The data collected immediately after hump installation and 6 months after virtually are indistinguishable.

Traffic flow and diversion

Traffic volumes generally decrease on streets where road humps have been constructed. For some streets, this was the reason the road hump was built. On other streets, the construction can have an unplanned and possibly undesirable impact. If speeders and heavy volumes of traffic are diverted to parallel streets, traffic operations may not be improved. Table 2 shows the magnitude of diversion from streets with road humps. As can be seen, there is a large range in the percent change in traffic volumes from pre-hump levels.

Diversion from streets with road humps appears to be uniform throughout the day and not merely during peak hours; although, 10-hour and 24-hour traffic volume counts for 46th Street in Washington, DC, showed a slight increase in diversion during nonrush hours. (*8*) On the surrounding streets, traffic volumes did in fact increase—in some cases between 3 and 4 percent—but the overall distribution of traffic appeared to improve. After road humps were constructed on 46th Street, traffic volume decreased 31 percent.

Speed changes on surrounding streets also are of interest. In one study, small changes were found in the 85th percentile speeds on two adjacent streets, with an overall net reduction suggested. However, the differences were not statistically significant. (*7*)

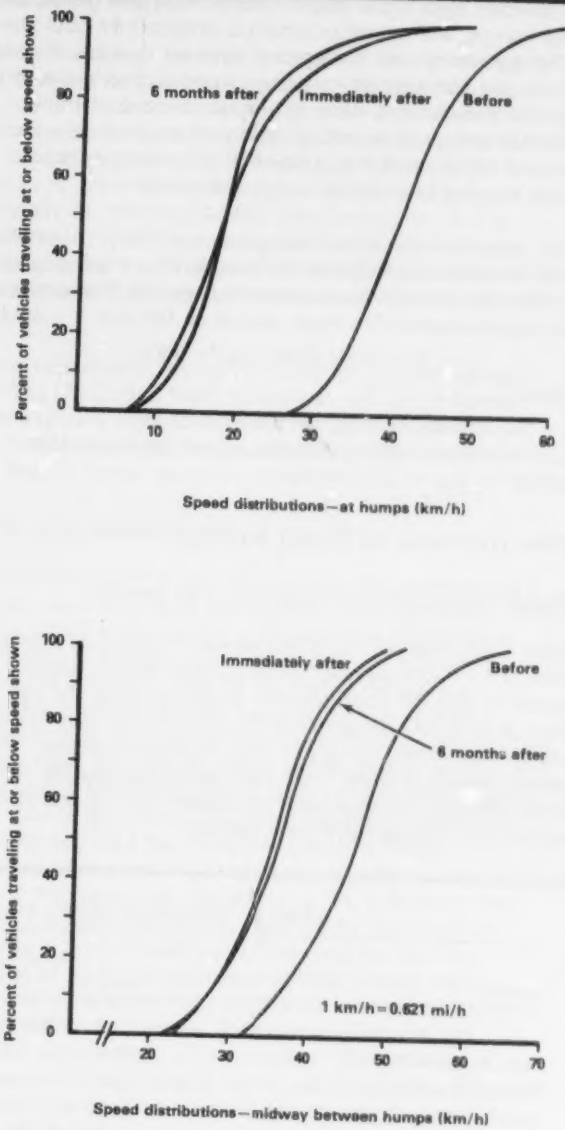


Figure 5.—Cumulative speed distributions before, immediately after, and 6 months after road hump construction. (6)

Safety of road humps

Road hump safety has been assessed by comparing accident data on the street before humps were constructed with accident data after construction. Some studies have included subjective assessments of the potential safety of humps, but the reliability of such assessments is questionable.

A study that used surrogate measures of safety showed significant decreases in conflicts between vehicles, pedestrians, and bicyclists after construction of road humps in Lund, Sweden.[2] In other studies, accident data taken at a number of locations indicate that accidents have not increased after installation of road humps; however, in general, the number of accidents at such locations is too small to perform statistical analysis.

Two studies in the United Kingdom, which has the most experience with road humps, have evaluated the surrounding streets as well as the streets with road humps to evaluate accident experience. An overall 14 percent net improvement in accident experience may be attributed to the construction of road humps. (*9, 10*)

One study (*11*) indicates that road humps can increase pedestrian safety gaps; yet another study (*12*) indicates that drivers spend less time looking for pedestrians and other vehicles and concentrate instead on the road humps themselves. The overall impact of these findings on safety is unknown.

Signing and marking requirements

Signs and markings are used with road humps to warn drivers so they will approach a single road hump or the first hump in a series at a smooth speed. Signs and markings also provide legal protection to the construction authority.

If signs and markings are poorly visible or located too far from the road hump, it is likely that a driver will not respond appropriately when traversing the hump. Oversigning or using markings that are too conspicuous also can have a detrimental effect by distracting and confusing the driver. In addition to safety considerations, excessive signs or high-reflectance signs and markings can pose esthetic problems for many residential neighborhoods.

No specific research has been reported that discriminates one set of markings and signs from others, nor has there been any universal acceptance of particular marking and signing configurations. Symbolic signs with verbal messages are used at most European road hump constructions (fig. 6). (*9*) Markings generally consist of solid white paint covering the entire hump. In areas without overhead lighting, reflective beads are embedded in the paint.

Australia and England use the word "hump" on signs; the United States uses the standard "Manual on Uniform Traffic Control Devices" (MUTCD) "BUMP" warning sign, W8-1. (*13*) Markings usually include a number of parallel longitudinal stripes on the road hump, characteristic of "zebra" crosswalks (fig. 7). (*5*)

Table 2.—Magnitude of traffic volume changes on streets with road humps

Location	"Before" volume	"After" volume	Percent change
10-hour count			
Barlanark Road (UK)	387	141	−64
16-hour count			
Cuddesdon Way (UK)	4,560	2,066	−55
Motum Road (UK)	713	472	−34
Palace Road (UK)	3,457	2,818	−18
Abbotsbury Road (UK)	6,050	4,172	−31
South Park/Moorfield Drive (UK)	4,288	1,977	−54
College Walk (UK)	2,594	2,436	−6
Esplande (UK)	1,978	1,955	−1
Albron Street (UK)	1,55[illegible]	[illegible],326	−15
24-hour count			
Rosewall (AUS)	1,038	786	−24
Norlane (AUS)	558	431	−23
Hawthorn (AUS)	2,468	1,254	−49
Dianella (AUS)	4,085	2,077	−49
Washington, DC (USA)	8,174	5,450	−33

Figure 6.—Symbolic sign and supplementary plate in conjunction with road humps in the United Kingdom. (10)

[2]C. Hyden and P. Garder, "Further Development of a Traffic-Conflicts Technique and Research on Speed-Reducing Measures," paper presented at the 61st annual meeting of the Transportation Research Board, Washington, DC, January 1982.

Other sign variations include the internally illuminated signs used in the United Kingdom; marking variations include using a series of longitudinal or transverse markings before the individual road humps or placing on-road messages such as "BUMP" adjacent to the road hump (fig. 7).

The degree to which markings and signing contribute to the overall effectiveness of road humps is unknown. However, researchers do seem to agree that road humps cannot be used safely without signs and markings.

Other considerations

Other relevant issues that should be considered in a thorough study of the operational effects of road humps include the following:

- Lateral placement of vehicles.
- Gutter running of vehicles.
- Hump damage.
- Major design variations such as raised pedestrian crossings.
- The comparative advantages of other traffic control devices for controlling speed (for example, chokers).
- The design of road humps for vehicles with long wheelbases such as firetrucks, buses, and trucks.
- Environmental issues such as noise levels and fuel emissions.

Viewpoints of Users and Potential Users

Early in 1983, the Traffic Division of the City of Thousand Oaks, California, surveyed U.S. cities and counties to determine the prominence of road hump usage in the United States, the perceptions of local officials and the engineering community on the benefits and problems of road humps, opinions on standardizing and codifying road humps, and whether additional research and development on road humps is merited.

Questionnaire and sample

The questionnaire used consisted of four parts: Information on the respondent's profession and jurisdiction, general information on usage and direct experience of the respondent with road humps, attitudes regarding the benefits of including road hump specifications into State or national manuals on traffic control devices (including the need for more research and development), and detailed information on existing road hump installations including evaluative data.

The sample was drawn from all jurisdictions that had requested a copy of a 1981 report on residential street improvements (7), participants in two University of California conferences on road humps, and all city traffic engineers in the State of California. From approximately 600 solicitations sent nationwide, 286 responses were received.

Figure 7.—Variation of road hump markings.

Direct experience and perceptions of road hump functions

Overall, 37 percent of the 286 respondents had driven over road humps. Respondents were asked whether road humps differed in any respect from speed bumps: Two percent indicated that there was no difference, 6 percent indicated that the humps differ only in size, and 10 percent noted other differences. However, 82 percent of the respondents indicated that humps and bumps have different functions.

Most appropriate uses of road humps

Seventy-five percent of the respondents indicated that humps should be used on two-lane residential streets with traffic volumes less than 10,000 vehicles per day, 66 percent indicated that humps should be used in parking lots, and 59 percent indicated that humps could be appropriately used on private roads.

Perceived benefits and problems with road humps

Benefits and problems were ascertained using responses to the question, "What do you perceive as the greatest benefits (or problems) with speed humps?" Respondents could indicate a "major benefit (problem)," "some benefit (problem)," or "unknown benefit (problem)" for several identified issues or specify additional issues.

Out of 12 potential benefits, 3 potential benefits—speed reduction in the vicinity of humps, speed reductions overall, and more effective than stop signs—emerged as being a "major benefit." Three potential benefits—increased property values, reduced noise, and improved air quality—were judged to be unachievable with road humps.

Out of 16 potential problems, 4 were found to be a "major problem," including increased liability and legal problems, the fact that humps are not an official traffic control device, the concern that if used on one street, other residents would want them, and the potential loss of vehicle control.

Comparisons were made to determine whether respondents without road humps in their jurisdictions differed in their ratings from those respondents with road humps. For respondents with road humps constructed in their jurisdictions, only the question of increased liability and legal problems remains a concern, although to date no legal history has developed for road hump usage. The "with road humps" group also indicated only one significantly different benefit: Speeds decreased between humps as well as in the vicinity of humps, an attitude not shared by the "without road humps" group. Nearly all of the "with road humps" respondents also cited reduced traffic volumes, greater diversion of nonlocal traffic, fewer complaints from citizens, reduced demands for enforcement, and accident reductions. Only one respondent in a jurisdiction with road humps felt that humps could present "a dangerous condition to a reasonable driver." In this respondent's jurisdiction, however, the road humps were atypical (10 ft [3.0 m] long and 6 in [152 mm] high).

Safety is the prominent issue seen by different respondents as being both a potential benefit and a potential problem. Speed-related issues, which can be associated with safety and changes in environmental quality, and property values and public acceptance issues also were perceived by some respondents as positive and by others as negative. The issues related to traffic planning and operations were more diverse. No respondent suggested a reduction in maintenance activities following construction of road humps, although a number of potential problems were cited. Nearly 90 percent of the respondents cited liability as a major constraint in constructing road humps; this concern is closely linked to the absence of authoritative standards or warrants for the construction and placement of road humps. Reduced police monitoring and enforcement of speed limits were cited as benefits to local government.

Are warrants and specifications needed?

Because of the concern voiced by various traffic engineers that warrants and specifications are needed to prevent a snowballing of requests for road humps (*14*), the questionnaire asked whether warrants and specifications are needed and whether additional research and development is needed before warrants and specifications can be developed.

The majority of respondents indicated that uniform sign specifications should be developed; approximately one-third of the respondents felt that no additional research and development was needed for signing, although virtually no hump signing research has been performed. Less than 50 percent of the respondents indicated a need for specifications/warrants dealing with design, placement, and markings for road hump use.

Review of responses from jurisdictions with road hump installations

Approximately 80 percent of hump installations are 12 ft (3.7 m) long by 4 in (101.6 mm) high. Six of the jurisdictions have lowered hump heights to 3 to 3.5 in (76.2 to 89 mm).

Costs vary from $200 per hump to more than $1,800 per hump, with an average of $866.

The signs used in conjuction with humps vary greatly, ranging from symbolic signs with one or two humps to word messages such as "Undulations Ahead." The most common signed message is the MUTCD standard bump warning sign. (*13*) Also, advance warning signs vary in distance from the hump; some jurisdictions locate warning signs at intersections of streets with humps installed.

Road markings used also vary. Some humps have no markings; others have longitudinal, lateral, or diagonal markings or combinations of markings.

Conclusion

Road humps are a viable means of controlling speeds of passenger vehicles on residential streets. The preponderance of evidence indicates that judicious placement of these devices can enhance safety and improve traffic distribution.

If hump use becomes more widespread, signs, markings, and construction practices will have to be standardized. Widescale adoption of optimal designs for road humps will require additional research and incorporation into State and, possibly, national authoritative documents on uniform traffic control devices.

REFERENCES

(1) G.R. Watts, "Road Humps for the Control of Vehicle Speeds," TRRL Report LR597, *Transport and Road Research Laboratory*, Crowthorne, Berkshire, England, 1973.

(2) J.R. Jarvis, "Legal Aspects of Road Humps on Public Roads," Research Report ARRB No. 109, *Australian Road Research Board*, Victoria, Australia, 1980.

(3) H. Pettersson, "Pro Med Hastighets-dampande gyppi vagbanan pa tre gator i Goteborg (Speed, Reducing Bumps. Tests in Three Streets in Gothenburg)," VTI Report No. 176, *National Road and Traffic Institute*, Linkoping, Sweden, 1979.

(4) P. Laitakari and K. Alppivuori, "The Effect of a Hump and an Elevated Pedestrian Crossing on Vehicle Comfort and Control," Report No. 69, *Technical Research Center of Finland, Road and Traffic Laboratory*, Finland, May 1981.

(5) J.P. Clement, "Speed Humps and the Thousand Oaks Experience," *Traffic Engineering Division, City of Thousand Oaks*, California, September 1982.

(6) P.E. McDonald and J.R. Jarvis, "The Use of Road Humps on Residential Streets in the Shire of Corio," ARRB Internal Report No. AIR 335-2, *Australian Road Research Board*, Victoria, Australia, March 1981.

(7) D.T. Smith, Jr., and D. Appleyard, "Improving the Residential Street Environment," Report No. FHWA/RD-81/031, *Federal Highway Administration*, Washington, DC, May 1981.

(8) G.R. Jivatode and T. Burke, "Neighborhood Speed Control Demonstration Project," *District of Columbia, Department of Transportation*, Washington, DC, January 1982.

(9) R. Sumner and C. Baguley, "Speed Control Humps in Kensington and Glasgow," TRRL Report No. SR456, *Transport and Road Research Laboratory*, Crowthorne, Berkshire, England, 1979.

(10) C. Baguley, "Speed Control Humps—Further Public Road Trials," TRRL Report No. LR1017, *Transport and Road Research Laboratory*, Crowthorne, Berkshire, England, 1981.

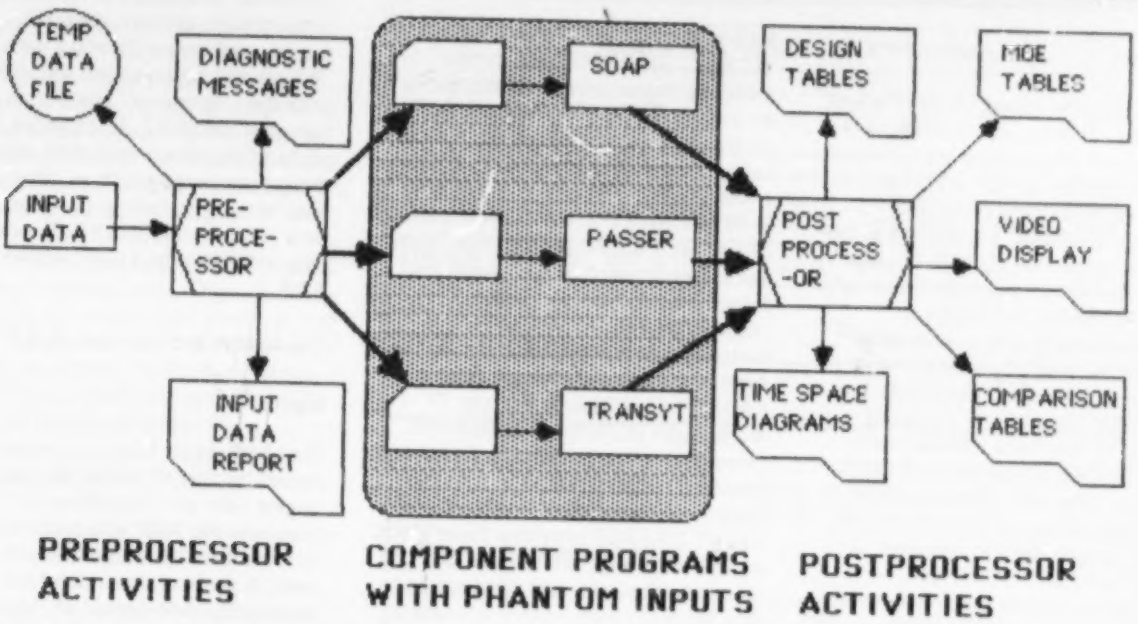
(11) R. Sumner and C. Baguley, "Speed Control Humps in Norwich and Haringey," TRRL Report No. SR 423, *Transport and Road Research Laboratory*, Crowthorne, Berkshire, England, 1978.

(12) B. Erikson and U. Horberg, "The Influence of Speed Reducing Bumps on Search Behavior of Road Users," Uppsala Psychological Report No. 284, *University of Uppsala, Department of Psychology*, Sweden, 1980.

(13) "Manual on Uniform Traffic Control Devices for Streets and Highways," Part II-C, "Warning Signs," *U.S. Department of Transportation, Federal Highway Administration*, Washington, DC, 1978.

(14) ITE Journal, "To the Editor," vol. 53, No. 5, June 1983, pp. 7-8.

Burton W. Stephens is a research psychologist in the Traffic Systems Division, Office of Safety and Traffic Operations R&D, Federal Highway Administration. He has extensive experience in human factors research and has been active in research involving the highway/motorist interface. Mr. Stephens, who serves as Deputy Division Chief, was on a professional exchange assignment with the Australian Road Research Board during 1986.



The Arterial Analysis Package

by

David R.P. Gibson and Llewellyn Williams

Introduction

The Arterial Analysis Package (AAP), conceived as a tool for timing traffic signals on arterial streets, gathers the most widely used design and analysis programs to provide a framework for solving signal timing problems using commonly available traffic engineering data.

Many traffic engineers already are using the AAP signal timing methods—the Signal Operations Analysis Package (SOAP), Progression Analysis and Signal System Evaluation Routine (PASSER), or Traffic Network Study Tool (TRANSYT) are all AAP component programs. They all, however, are used as independent programs with their own particular strengths and weaknesses. The AAP provides a common coding structure for arterial systems so that the component programs can be used from a common data file. In addition to the three component programs that form the engineering analysis core of the AAP a group of interactive and batch support programs is provided.[1]

This article discusses the three component traffic signal timing programs, the overall operation of the AAP, how to define a problem for analysis, how to prepare the input deck using the support programs, how to interpret results, and how the AAP was tested.

[1] C.E. Wallace, K.C. Courage, and D. Reaves, "Arterial Analysis Package," Report No. FHWA-IP-86-1, Federal Highway Administration, Washington, DC. Not yet printed.

Component Programs

SOAP 84

SOAP was developed for the Federal Highway Administration (FHWA) by the State of Florida and the University of Florida to provide a convenient yet powerful signal timing tool for analyzing individual intersections. (*1*)[2] The original SOAP (SOAP 79) was written in Fortran for mainframe computers, in BASIC for Apple II microcomputers, and in calculator notation for the Texas Instruments and Hewlett Packard hand-held programmable calculators. However, because of the wide differences in computational power between the versions, they differed somewhat in their methodologies and the degree of human intervention required. A second program, SOAP 84, developed a unified version for both mainframe and microcomputers (MS-DOS, IBM, and Apple Macintosh) using ANSI standard Fortran 77.

SOAP has three computational functions: Design, analysis, and evaluation. SOAP can assign and time up to six dials for various time periods. If actuated control is specified, no dial assignments are made. SOAP 84 does not select an "optimum" cycle length or phasing; the user must use the design and analysis capabilities to set up and evaluate designs to determine the best mix of measures of effectiveness (MOE's). SOAP provides four kinds of reports: Input data, signal design recommendations, MOE reports, and plots and diagrams.

[2]Italic numbers in parentheses identify references on page 96.

PASSER II-84

PASSER II, which evolved from SIGART, SIGPROG, and mathematical programming techniques, is an arterial signal progression optimization program based on the concept of maximizing the green bandwidth available to traffic. PASSER II-84 release 3.0 is the current version of PASSER available from the Texas State Department of Highways and Public Transportation. Texas cooperates with FHWA to ensure that the version of PASSER II in the AAP is the current release version. PASSER II, written in Fortran 77, works with multiphase signals and calculates phase lengths, offsets, and demand/capacity ratios at intersections to evaluate their levels of service. (*2*) PASSER provides three kinds of reports: Input data, signal design recommendations, and time-space diagrams.

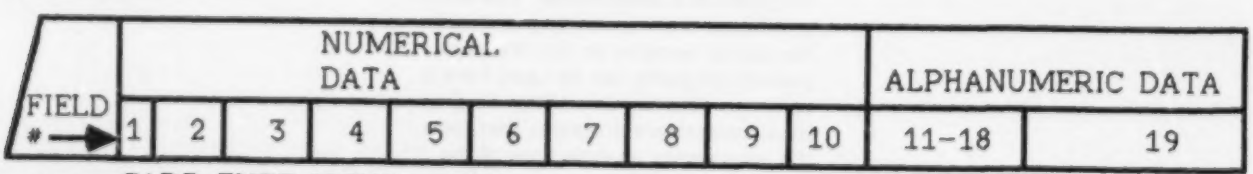
TRANSYT-7F

TRANSYT-7F is a signal progression optimization program for networks based on the concept of minimizing traffic delays and stops. TRANSYT-7F release 4 is the current version of TRANSYT available from FHWA. (*3*) TRANSYT-1 was written in assembly language in 1967. Since then, the program has been improved by recoding into Fortran, adding multiphase analysis, enhancing input error checking, adding automatic calculation of initial signal timing, providing multiple links at single stop lines, adding bus analysis and fuel consumption, and, in version 7F, "Americanizing" the input. TRANSYT-7F varies offsets and splits in user-specified time increments, analyzes the results with a deterministic platoon dispersion model, and keeps iterating with a "hill climb" optimization algorithm until the "optimum" solution is obtained. TRANSYT-7F provides five kinds of reports: Input data, signal design recommendations, time-space diagrams, a performance table, and flow profiles. TRANSYT-7F analyzes only arterials when used within the AAP.

Description of the AAP

Inputs

The AAP input coding scheme is based on that of SOAP 84. Each card begins with an "identification" field that tells the AAP what kind of data to expect on the remainder of the card. A two-column numerical field (to identify time period or duration), a five-column numerical field (to identify begin time or intersection number), and eight five-column fields for variables (usually data by movement) follow. The last 25 columns are for alphanumeric variables—usually one-column directional indicators such as N, S, E, W, T(hru), and L(eft) and labels for use in headings. By using the same structure for all kinds of cards, it is easier to learn the coding scheme and to spot errors. Typical cards—the SETUP card and the VOLUME card—are shown in figure 1. The coding format allows the same "card deck" to be used for both PASSER and TRANSYT with minimal changes.



SETUP		1	12	60			1.6			N	
C NAME	BEGIN	TIME	NBT	NBL	SBT	SBL	EBT	EBL	WBT	WBL	EXAMPLE ROAD
VOLUME		0700	1500	100	1500	100	1500	100	1500	100	LABEL-IF DESIRED
VOLUME		0800	1500	100	1500	100	1500	100	1500	100	EXAMPLE DATA
CAPACITY		0700	1.8	0.5	2.0	1.5	2.0	1.0	2.0	1.0	

Figure 1.—AAP input card format.

Outputs

A major problem with using SOAP, PASSER, and TRANSYT before the AAP was developed was in mentally converting from one set of outputs to another while evaluating the results. A consistent set of 80-column output formats was developed for each of the three component programs, which allows the outputs to be spread side by side so that the results can be compared easily (figs. 2-4). Although the MOE's generated by the programs are not identical, they are now comparable, facilitating translation of the program outputs to traffic signal controller settings.

AAP structure

The AAP structure (fig. 5) consists of data input managers (DIM's) to create the input data card deck; the card deck; the preprocessor, which maps the card deck to the temporary data file, performs diagnostic checking, and then creates input card decks for one or more component programs; the three component programs; the postprocessor, which creates the information for creating graphic displays on microcomputers and transmits information between PASSER and TRANSYT; and the microcomputer-based graphic display programs.

Defining a Problem for Analysis

The AAP can define two kinds of problems: A single-intersection, multiperiod analysis with SOAP and a multiple-intersection, single-period analysis using PASSER and TRANSYT to optimize signal progression. The same general file structure (a three-dimensional array) is used for both problems.

For multiple-intersection, single-period analysis, a SETUP card is defined (fig. 6) with the file definition as multiple intersection, the number of intersections, the period length, the progression speed, if signal-timing information is to be entered in seconds or percent of cycle, the orientation of the artery (N, S, E, or W), and the arterial name. Next, the ARTERIAL card tells the AAP whether to run PASSER or TRANSYT. The MAP cards establish

SYSTEM TOTAL MEASURES OF EFFECTIVENESS

ARTERIAL: SKILLMAN AVENUE BY: TRANSYT

PERFORMANCE MEASURES	TOTAL TRAVEL (V-MI)	TOTAL TIME (V-HR)	TOTAL DELAY (V-HR)	AVG. DELAY (SEC/V)	UNIFORM STOPS NO. (%)	FUEL CONS. (GA)	SYSTEM SPEED (MI/H)	PERFORMANCE INDEX
<TOTALS>	3009.88	183.14	97.07	27.5	9298.(73)	244.86	27.82	129.98

Figure 2.—TRANSYT system MOE's.

SYSTEM TOTAL MEASURES OF EFFECTIVENESS

ARTERIAL: SKILLMAN AVENUE BY: PASSER II

BANDWIDTH RESULTS	CYCLE LENGTH (SEC)	BANDWIDTH EFFICIENCY (%)	ATTAIN-ABILITY (%)	THRU BANDWIDTHS (SEC)	PROGRESSION SPEEDS (MPH)
SYSTEM :	95	38	100	71	
NORTH BOUND :		35	-	33	31
SOUTH BOUND :		40	-	38	35

PERFORMANCE MEASURES	TOTAL VEHICLES (VEH/HR)	TOTAL DELAY (VEH-HR)	AVERAGE DELAY (SEC/VEH)	TOTAL STOPS (VEH/HR)	(%)	FUEL CONSUMPTION (GAL/HR)	MAX MIN CYCLE (SEC)
TOTALS :	12717.	97.7	27.7	8724.	(69)	398.3	94

Figure 3.—PASSER system total MOE's.

ARTERIAL SUMMARY

ARTERIAL: SKILLMAN AVENUE BY: PASSER II

INTERSECTION NO.	NAME	MAX V/C (%)	TOTAL DELAY (V-HR)	AVG. DELAY (SEC/V)	TOTAL STOPS (VEH/H)	(%)
1	MOCKINGBIRD :	88	38.55	35.1	3287.(83)	
2	UNIVERSITY :	71	7.86	12.0	773.(33)	
3	LOVERS LANE :	82	27.67	26.2	2625.(69)	
4	SOUTHWESTERN :	89	23.63	32.7	2038.(78)	
TOTAL SKILLMAN AVENUE :		89	97.71	27.7	8723.(69)	

Figure 4.—PASSER arterial summary.

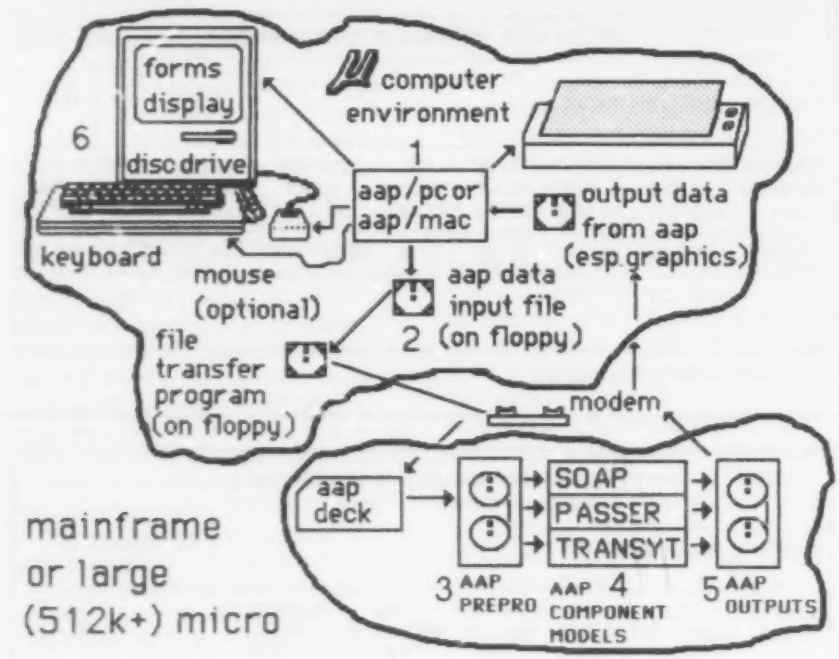


Figure 5.—AAP data flow and structure.

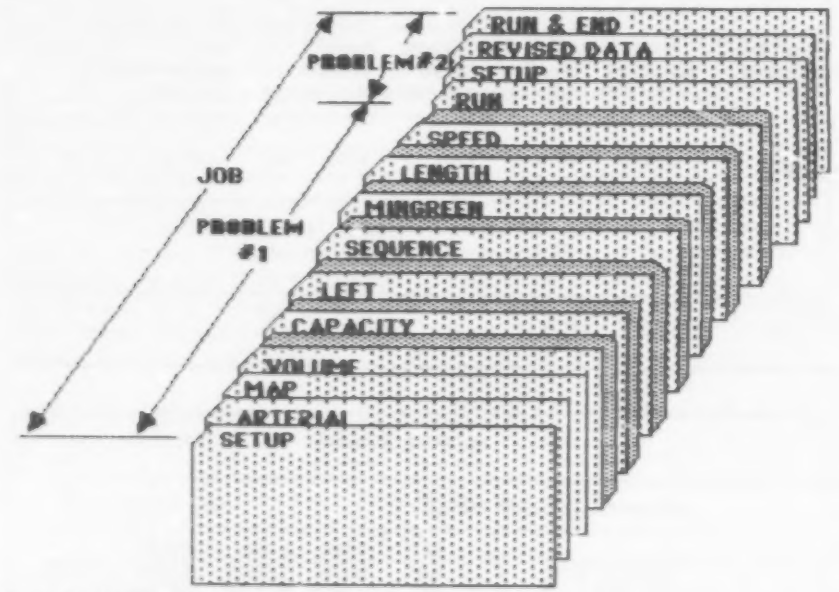


Figure 6.—AAP data deck structure.

the sequence number, the intersection reference number, and the name of each intersection. The VOLUME cards follow and provide the intersection reference number and traffic volumes for each of the intersection's movements. The CAPACITY cards then define the capacity for each movement either as a number of lanes (for example, 1, 2.0, or 3.4) or as saturation flow rates. LEFT cards are entered to describe permissive and restrictive left-turn movements or the lack of these movements. MINGREEN cards are needed if minimums for any movements differ from the default values—15 seconds for through movements and 10 seconds for left-turn movements. Because pedestrian volumes, intersection geometry, and local policies strongly affect these values, this optional card usually will be present. The LENGTH cards are used to give the distance from the stopline to the upstream stopline for the arterial approaches. The SPEED card gives the approach speed in miles per hour for each approach. The RUN card tells the computer that all the data have been entered, and the run should be made. The RUN card also specifies a case number and whether an optimization, evaluation run, actual run, or just an input data check is desired. The card also provides for an optional title for the run. The END card signals the computer that no more data for additional runs are in the data deck and that the AAP should terminate execution.

Preparing the Input Deck

The AAP input deck can be prepared in two ways. Traditionally, data are written on coding forms and then IBM cards are keypunched on a machine. This method, however, is being superseded by the use of DIM's, interactive data input programs written in BASIC or Fortran 77 on MS-DOS, Apple II, or Apple Macintosh microcomputers. The data coding form is replaced with a data collection form (fig. 7) organized to collect most of the data relevant to an individual intersection on one page for easy reference and entry into the DIM.

An AAP forms program hastens the creation of the initial AAP deck for single-period arterial analysis. The first menu in AAP forms allows the user to begin a new problem, enter input data, prepare an AAP input file, select an AAP input file, or exit. If "enter input data" is selected, the user has the option of dealing with the problem-description data, the intersection-oriented data, or the approach data; specifying tables or plots to be printed; or providing run data. Sub-menus then allow the data to be entered in a tabular format similar to a spreadsheet.

The AAP DIM edits individual data cards, enters multiple-run or multiple-period data, and enters special cards not provided for in the AAP forms program (figs. 8 and 9).

After the AAP input deck has been prepared, it is transmitted to a mainframe computer for execution by the AAP using a modem program. A larger microcomputer (IBM PC or XT with 256k bytes of memory or an Apple Macintosh 512k or plus) can execute the AAP directly.

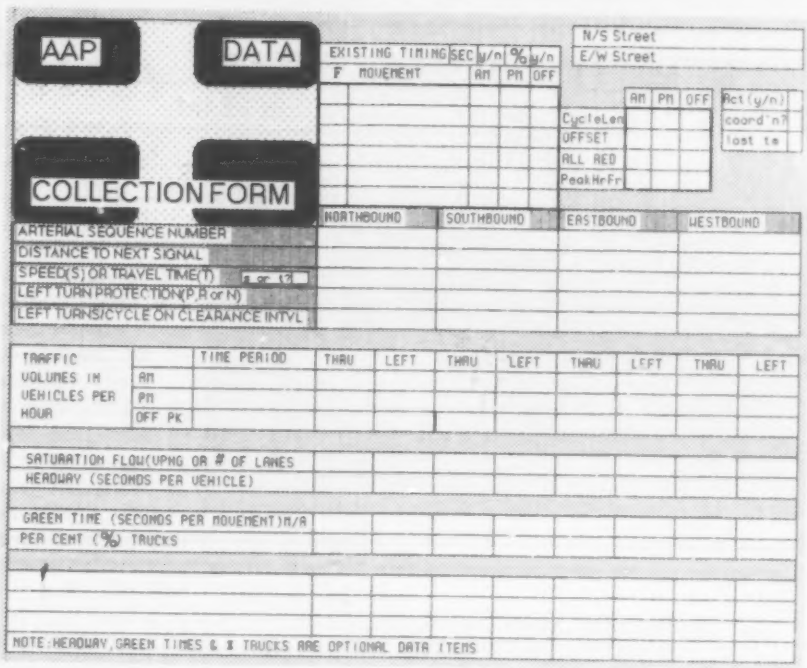


Figure 7. — Data collection form.

Interpretation of Results

The AAP outputs were designed to be listed on an 80-column CRT screen or printed on 80-column paper. This allows tables to be inserted conveniently into standard-sized 8½- × 11-in reports. The major sets of results are: Input data reports, performance evaluations, signal timing, time-space diagrams, platoon dispersion diagrams (under development),[3] and error/warning messages.

There are three input data reports. The input data echo, an echo of the input cards exactly as they were read into the program without any preprocessing, allows the user to see where any errors occur in the input deck. The global parameters allow the user to review the data set up for the entire system in a structured and commented fashion. The approach-specific parameters provide the same function for the data for each individual intersection. Because not all input data are relevant to all AAP component programs, some parameters may not be relevant for particular runs. Default values for nonspecified parameters will be provided.

Performance evaluation of a design is critical to determine what will happen if the design is implemented. Intersection MOE reports are available from SOAP, PASSER, and TRANSYT; system total and arterial summary MOE reports are available from TRANSYT and PASSER (figs. 2-4).

If the MOE results are satisfactory, then the signal timing can be implemented. The single-intersection signal timing tables from SOAP and the system signal timing plans and intersection timing plans from PASSER and TRANSYT provide detailed information on phase lengths, percent of cycle, and (for electromechanical controllers) pin settings. Engineers can adjust the offsets to increase the "perceived" progression with minimal damage to the MOE's.

Validation and Availability

The AAP component programs have been in widespread use since 1979 when SOAP was introduced as a signal timing tool for isolated intersections. The GASCAP program in the State of Florida demonstrated the use of SOAP for practical applications. The State of Texas has used the PASSER program as a maximal bandwidth coordination tool since the early 1970's. As a mathematical algorithm, PASSER has been shown to produce very usable results. The TRANSYT model was used by the State of Kentucky in a signal timing study and produced reasonable results, with MOE's comparable to those of Netsim, SIGOP III, and field data. A similar study in Overland Park, Kansas, also found TRANSYT-7F to give good MOE data comparable to field data and other optimization models evaluated. As a result, it was decided that TRANSYT-7F would be the "evaluation" tool in the AAP.

[3]Courage et al., "Platoon Progression Diagram User's Manual," prepared for the Federal Highway Administration course on the AAP, Washington, DC, 1984.

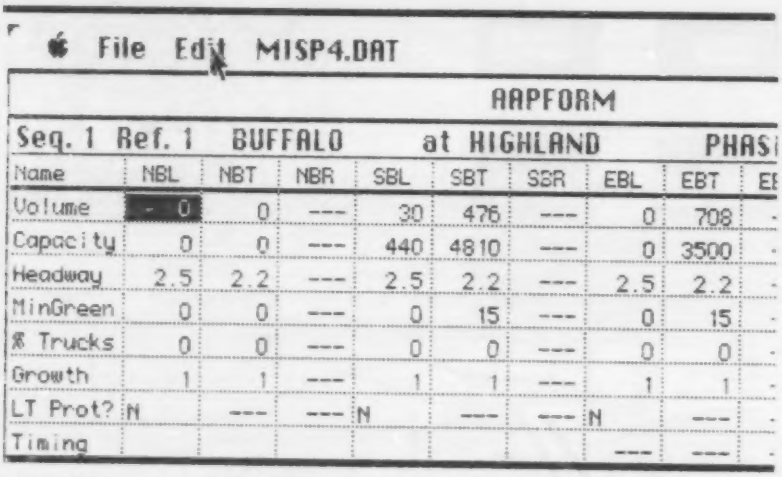

File Edit MISP4.DAT
AAPFORM
Seq. 1 Ref. 1 BUFFALO at HIGHLAND PHAS
Name NBL NBT NBR SBL SBT SBR EBL EBT
Volume 0 0 --- 30 476 --- 0 708
Capacity 0 0 --- 440 4810 --- 0 3500
Headway 2.5 2.2 --- 2.5 2.2 --- 2.5 2.2
MinGreen 0 0 --- 0 15 --- 0 15
% Trucks 0 0 --- 0 0 --- 0 0
Growth 1 1 --- 1 1 --- 1 1
LT Prot? N --- --- N --- --- N ---
Timing --- ---

Figure 8.—AAP forms—intersection data screen.

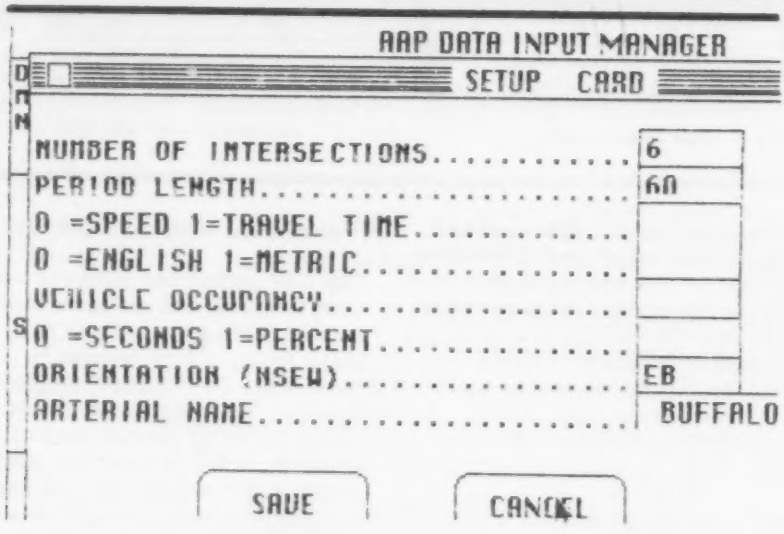


Figure 9.—AAP DIM edit card screen.

The mainframe version of the AAP (version 2.0) is available on a trial basis from the Federal Highway Administration, Office of Implementation, HRT-20, 6300 Georgetown Pike, McLean, Virginia 22101-2296. The microcomputer versions are available on floppy disk from the McTrans Support Center, University of Florida, 346 Weil Hall, Gainesville, Florida 32611, for IBM PC's and Apple Macintosh microcomputers. DIM's for the AAP are available for the IBM, Apple Macintosh, and Apple II microcomputers.

A 3-day training course on the AAP is available for a fee of $4,000 from FHWA's National Highway Institute. Please contact Mr. Ron Giguere, Federal Highway Administration, Office of Traffic Operations, HTO-23, 400 7th Street, SW., Washington, DC 20590; telephone: (202) 366-2203. The course may be taught in any of three ways depending on the availability of microcomputers. If a microcomputer laboratory with 12 or more IBM and/or Apple microcomputers is available, then a microcomputer-based "hands on" course can be presented. If only a few microcomputers are available and a laboratory setting is not available, then a mainframe-based course with microcomputer demonstrations can be presented. If no microcomputers are available, then a mainframe-based course will be given.

REFERENCES

(1) K.C. Courage and D. Reaves, "Signal Operations Analysis Package," Report No. FHWA-IP-85-7, *Federal Highway Administration*, Washington, DC, January 1985.

(2) "PASSER II-84 Users Manual," Report No. FHWA/TX-84/50+375-1F, *Texas State Department of Highways and Public Transportation*, Austin, TX, 1984.

(3) Wallace et al., "TRANSYT-7F User Manual," *Federal Highway Administration, Office of Traffic Operations*, Washington, DC, June 1984.

David R.P. Gibson is a traffic engineer with the Safety and Traffic Implementation Division, Office of Implementation, Federal Highway Administration. He is project manager of the Arterial Analysis Package project and is responsible for technology transfer activities on traffic signal controller hardware and timing. Before joining the Office of Implementation, Mr. Gibson was a traffic engineer for the District of Columbia.

Llewellyn Williams is a traffic engineer with the Safety and Traffic Implementation Division, Office of Implementation, FHWA, where he is responsible for technology transfer activities in traffic and safety. Before joining the Office of Implementation, Mr. Williams was head of traffic operations for the State of West Virginia.

Technology Transfer Laboratory

The Federal Highway Administration (FHWA) Offices of Research, Development, and Technology (RD&T) have established a **Technology Transfer Laboratory** at the Turner-Fairbank Highway Research Center in McLean, Virginia. Operated by the Office of Implementation, the purpose of the Laboratory is to investigate and facilitate new methods for technology transfer (T^2), including more effective and efficient promotion of new technology, better communication to the highway community, and faster response to FHWA and State requests for assistance. The Technology Transfer Laboratory currently includes office space, a computer-user area, a photologging work station, a slide preparation area, and classroom space.

During the developmental stage of the Laboratory, microcomputer assistance services were provided—testing and evaluating applications software; testing new microcomputers and related hardware; investigating new uses for microcomputers to support T^2; and providing consultation and support for microcomputer users throughout FHWA. In the future, this assistance function will focus primarily on investigating new microcomputer hardware and software and new ways to support T^2 effectively as the use of microcomputers by the FHWA staff increases.

When fully operational, the Laboratory will be staffed by FHWA personnel and a support services contractor. Electronic devices and concepts, such as computer-generated graphics systems, microcomputer/laser disk interfacing, and microcomputer display systems, will be evaluated and adapted in the Laboratory to reduce the cost of T^2. The support services contractor will help develop the electronic devices and concepts selected and prepare the operation and maintenance procedures to ensure continued use of the systems. The contractor also will assist with onsite operational support for these devices and concepts.

Expert systems represent a promising technology that is expanding rapidly in many industries but has not reached widespread use in the highway engineering field. FHWA's Technology Transfer Executive Committee has recommended that the Technology Transfer Laboratory be the focal point for expert systems development in FHWA, serve as a clearinghouse for information on expert systems, and assist with systems developed by the Offices of RD&T and the FHWA T^2 offices. The Technology Transfer Laboratory is providing training for FHWA personnel and is developing the capabilities—hardware, software, and expertise—for evaluation and development of expert systems.

Traffic control systems equipment, displayed in the Technology Transfer Laboratory at the May 1985 Open House at the Turner-Fairbank Highway Research Center.

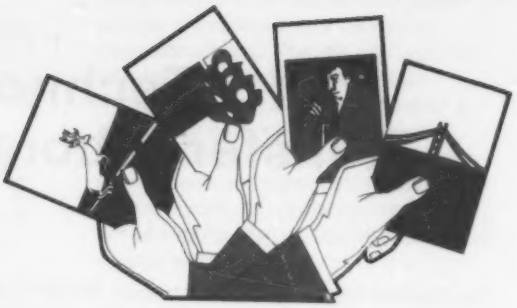
Expert systems will provide effective support for diagnosis, design, decisionmaking, and training. Currently, three expert systems are being developed under the sponsorship of FHWA: "An Expert System for Asphalt Concrete Construction," a joint venture between FHWA and the Corps of Engineers' Construction Engineering Research Laboratory to support asphalt construction inspection, including asphalt mixes, plant operation, weighing, laydown, and compaction; "Application of Artificial Intelligence to Urban Congestion Problems," to assess the feasibility of and recommend an approach for developing artificial intelligence tools for reducing congestion and improving throughput in major highway corridors; and "EXPAVE: A System to Assist the Design Engineer in Concrete Pavement Evaluation and Rehabilitation."

The Technology Transfer Laboratory is developing a slide library to store slides and associated text for the FHWA T^2 Program. This library will be maintained by the support services contractor and will be available to FHWA personnel. An optical disk system will be used for storage and rapid access to the slides and text.

Long-range communications plans include developing full teleconferencing facilities to improve methods of T^2 to remote locations, which could augment T^2, training, and general information exchange with the field.

Further information on the Technology Transfer Laboratory can be obtained by contacting:

Messrs. Jim Wentworth or Bob Ellington
FHWA, Office of Implementation
Safety and Traffic Implementation Division, HRT-20
6300 Georgetown Pike
McLean, Virginia 22101-2296
Telephone: (703) 285-2511 or 285-2512



Recent Research Reports You Should Know About

The following are brief descriptions of selected reports recently published by the Federal Highway Administration, Offices of Research, Development, and Technology (RD&T). The Office of Engineering and Highway Operations Research and Development (R&D) includes the Structures Division, Pavements Division, and Materials Division. The Office of Safety and Traffic Operations R&D includes the Traffic Systems Division, Safety Design Division, and Traffic Safety Research Division. The reports are available from the source noted at the end of each description.

Requests for items available from the RD&T Report Center should be addressed to:

Federal Highway Administration
RD&T Report Center, HRD-11
6300 Georgetown Pike
McLean, Virginia 22101-2296
Telephone: (703) 285-2144

When ordering from the National Technical Information Service (NTIS), use PB number and/or the report number with the report title and address requests to:

National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

Cost-Effectiveness of Sampling and Testing Programs, Executive Summary, Report No. FHWA/RD-85/029, and Final Report, Report No. FHWA/RD-85/030

by Materials Division

These reports present the results of a study to develop a new model and computer program for improving the cost-effectiveness of sampling and testing programs. The new program, COSTOP1, is used to establish priorities among quality control tests and to optimize sampling frequencies for each test. The model considers the cost of testing, the impact of testing changes on construction practice, the effect of a material property (test result) on pavement performance, and maintenance strategy and cost in determining the cost-effectiveness. The program is modular, allowing users to substitute their own cost data, maintenance strategies, and performance models.

The reports may be purchased from NTIS (PB Nos. 86 243995 and 86 155199).

Behavior of Piles and Pile Groups Under Lateral Load, Report No. FHWA/RD-85/106

by Materials Division

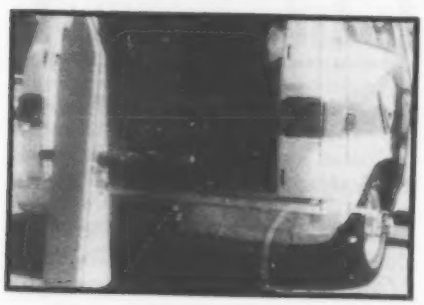
Several methods of analysis and design of piles under lateral loading are in use. Presumptive values that suggest allowable, but conservative, loads are included in some manuals of practice. For example, batter piles may be used with an assumption, not entirely correct, that no lateral load is taken by vertical piles. Several rational methods in which the equations of mechanics are satisfied have been proposed and are reviewed in this report.

The rational method uses different equations to solve the governing differential equation along with the use of nonlinear curves to describe the soil response. Curves showing soil resistance "p" as a function of pile deflection "y" have been recommended for several kinds of soil and pile loading.

Case studies are presented in which results from analysis are compared with results from experiment. Design recommendations are made, and needed research is outlined.

The report may be purchased from NTIS (PB No. 86 238466).

Rapid Nondestructive Delamination Detection, Report No. FHWA/RD-85/051

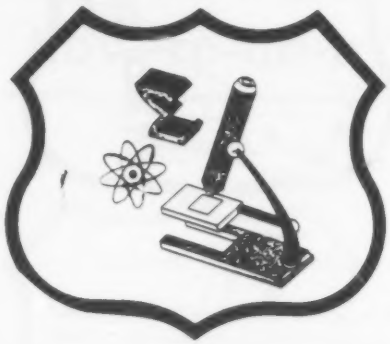


by Materials Division

Corrosion-induced delamination of bridge decks is a major problem in the United States. Early detection of delaminations can optimize the scheduling of maintenance and prevent costly repairs at a later date. This report discusses a study on assessing the delamination condition of inservice bridge decks without disrupting traffic. The radar field instrumentation system developed in the study was successful in detecting delaminations at a speed of 40 mi/h (64 km/h). The radar system also can be used at low speeds or in an essentially static mode to define the exact areas of concrete removal at the time of bridge deck rehabilitation. The system is suitable for decks overlaid with asphalt as well as bare concrete decks and is substantially independent of weather. Standing water has a disabling effect on the inspection signal, and it is doubtful that an inspection could be performed with puddles on the surface. However, damp pavement has virtually no adverse effect on the inspection signal.

The report may be purchased from NTIS (PB No. 86 177516).

Engineering Characterization of SULPHLEX Binders, Report No. FHWA/RD-85/032, and Chemical Characterization of SULPHLEX Binders, Report No. FHWA/RD-85/033



by Materials Division

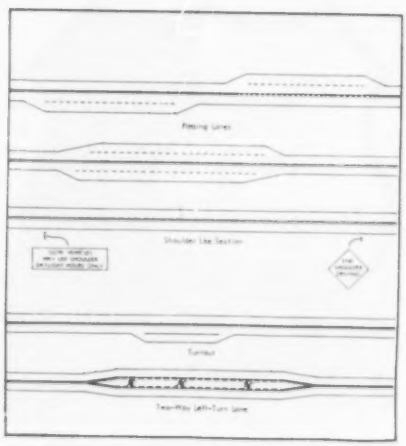
A chemically-modified sulfur called SULPHLEX (a trademark of Southwest Research Institute) consists of 70 percent elemental sulfur and 30 percent of a combination of hydrocarbons, which chemically react with molten sulfur. This chemical reaction allows the polymeric, molten sulfur to retain, at least to some extent, certain favorable engineering properties after cooling.

Report No. FHWA/RD-85/032 presents the results of an extensive engineering characterization including mixture design considerations; flexural fatigue; fracture potential; deformation potential; creep compliance and stiffness response; aging characteristics; and resilient and dynamic moduli properties. In addition, a pavement performance prediction of SULPHLEX as a paving material under various climates and traffic conditions was made using a systems pavement analysis approach.

Report No. FHWA/RD-85/033 discusses the chemical stability and characteristics of SULPHLEX.

The reports may be purchased from NTIS (PB Nos. 86 186483 and 86 182219).

Passing Lanes and Other Operational Improvements on Two-Lane Highways, Report No. FHWA/RD-85/028



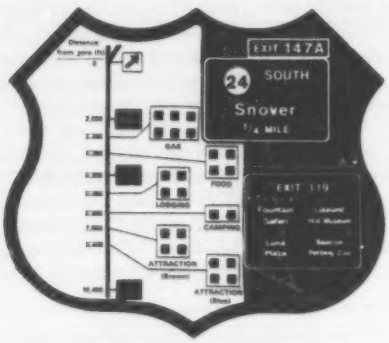
by Traffic Safety Research Division

Many rural two-lane highways experience operational problems related to high traffic volumes; lack of adequate passing opportunities; recreational and other slow-moving vehicles, such as schoolbuses and farm equipment; roadside development that generates turning maneuvers at driveways; and turning movements at intersections. This report evaluates five operational treatments to alleviate these problems: Passing lanes; short, four-lane sections; shoulder-use sections; turnouts; and two-way, left-turn lanes. Current signing, marking, and design practices used for these operational treatments in 13 States that participated in the study are reviewed. An operational evaluation of the treatments was based on field data collected at 35 treated sites, and a

safety evaluation of these treatments was based on accident data collected at 138 treated sites. The study concluded that all five operational treatments evaluated can improve traffic operations on two-lane highways at relatively low cost. Passing lanes; short, four-lane sections; and two-way, left-turn lanes also improved safety. Turnouts and shoulder-use sections had no effect on safety.

The report may be purchased from NTIS (PB No. 86 214293).

Effects of Supplemental Interchange Signing on Driver Control Behavior, Report No. FHWA/RD-86/077



by Traffic Safety Research Division

Research was conducted to determine the effect on driver behavior of supplemental interchange signing, including various combinations and numbers of tourist-oriented attraction and service signs. Thirty-six test subjects "drove" the Federal Highway Administration driving simulator on a simulated 40 mi (64 km) freeway with 14 interchanges with supplemental signing for attractions and services. Test subjects were asked to identify specific attraction and/or service signs when approaching interchanges. Data were collected for computer analysis regarding speed differential, erratic maneuver, acceleration noise, and recognition distance. The addition of the supplemental attraction signs generally was detrimental to driver control behavior. Field tests should be conducted to confirm the behavior effects. Driver age, sign spacing, and total number of supplemental signs per interchange should be examined during the field study. The sign designs also require refinement and further study.

The report may be purchased from NTIS (PB No. 86 199353).

Cost-Effectiveness of Countermeasures for Utility Pole Accidents, Report No. FHWA/RD-83/063

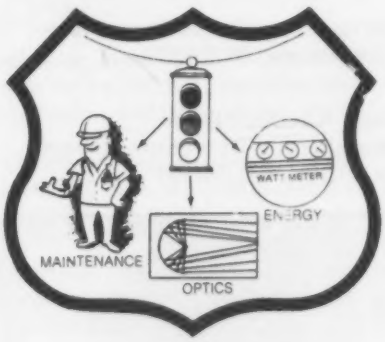
by Safety Design Division

The study described in this report was conducted to develop a cost-effectiveness analysis procedure for the optimal selection of countermeasures for utility pole accidents. Accident, traffic, and roadway data were collected and analyzed for over 2,500 mi (4 000 km) of urban and rural roads in four States. The results of the data analysis showed that lateral pole offset, traffic volume, and pole density were most highly related to utility pole accidents. A utility pole accident predictive model was developed.

Based on a cost-effectiveness analysis, undergrounding, pole relocation, and breakaway pole hardware were found to be cost-effective for telephone and electric distribution lines for various traffic and roadway conditions. Reducing pole density through multiple use also was cost-effective in some instances, but increasing pole spacing generally was not cost-effective. No countermeasures involving large transmission poles and lines were cost-effective within the limits of the analysis. General guidelines were developed for selecting cost-effective countermeasures. A computer program was developed for selecting optimal countermeasures for specific roadway sections.

The report may be purchased from NTIS (PB No. 86 181245).

Alternative Incandescent Traffic Signal Lamps and Systems for Improved Optical and Energy Efficiency, Report No. FHWA/RD-85/089



by Traffic Systems Division

This report discusses a study to determine methods of improving the optical efficiency of traffic signals to reduce power usage while maintaining high safety standards. Indepth investigations on the use of quartz-halogen lamps, low-voltage lamps, redesigned lenses, and nighttime signal dimming showed that all methods decreased power usage, although in some cases the increased initial cost did not justify their application. Very large efficiency gains were obtained using redesigned lenses, and these principles are described in the report.

Limited copies of the report are available from the RD&T Report Center.

Implementation/User Items "how-to-do-it"

The following are brief descriptions of selected items that have been completed recently by State and Federal highway units in cooperation with the Office of Implementation, Offices of Research, Development, and Technology (RD&T), Federal Highway Administration. Some items by others are included when the items are of special interest to highway agencies.

When ordering from the National Technical Information Service (NTIS), use PB number and/or the report number with the report title and address requests to:

National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

Cost-Effective Inventory Procedures for Highway Data: Users Manual, Report No. FHWA-IP-85-14

by Office of Implementation

This users manual was developed to aid in selecting cost-effective inventory procedures for highway data. The experiences of highway agencies and other users were analyzed to determine advantages and disadvantages of alternative inventory procedures. A cost analysis was performed for these procedures under various roadway, population density, and other system characteristics conditions, and a procedure for selecting the most cost-effective inventory method was developed.

The manual may be purchased from NTIS (PB No. 86 196953).

Model Procedure for Inservice Evaluation of Roadside Safety Hardware Devices, Report No. FHWA-IP-86-8

by Office of Implementation

This report presents procedures for conducting inservice evaluations of roadside safety hardware devices. Part I of the report reviews the planning process, identifies key elements required in an evaluation work plan, and outlines the responsibilities of various State agencies. It also describes the process for selecting sites, installing hardware devices, analyzing evaluation data, and reporting the findings. Part II of the report consists of sample work plans for the following roadside safety appurtenances: Eccentric loader breakaway cable terminal, IBC barrier system, controlled release terminal, and the self-restoring traffic barrier (SERB) median barrier.

The report may be purchased from NTIS (PB No. 86 195906).

Calibration Procedures for Roadmeters, Report No. FHWA-TS-86-201

by Office of Implementation

This report discusses a research project conducted to evaluate the performance of an inexpensive, noncontact roughness measuring device—the Roughness Surveyor—as well as the potential use of this device as a calibration reference for response-type road roughness measuring (RTRRM) systems. RTRRM systems from Georgia, Florida, and Minnesota were correlated against the Roughness Surveyor, the inertial profilometer owned by the Ohio Department of Transportation, and the profilometer designed and operated by the South Dakota Department of Transportation.

Sixteen test sites were selected for the correlation and calibration study, with 52 individual test sections encompassing a variety of roughness levels and pavement surfaces. The results of the roughness testing showed an excellent correlation between all of the devices. The standard error of estimate, however, was rather large for some of the linear regression equations. An analysis of serviceability of index ratings from the Florida, Ohio, and South Dakota units indicated that different values were obtained between the units on the same test sections.

The evaluation of the Roughness Surveyor indicated that the roughness results obtained were insensitive to speed variations. Problems were encountered with obtaining valid roughness readings on extremely rough textured surfaces, such as surface treatment. The testing repeatability of the Roughness Surveyor was not as good as that obtained with the Ohio profilometer and slightly better than two of the three RTRRM systems. The day-to-day variability was much higher for the Roughness Surveyor than for the Ohio profilometer and the RTRRM systems.

The report may be purchased from NTIS (PB No. 86 246642).

Mobile Reflectance Checker for Snowplowable, Raised Pavement Markers

by the Ohio Department of Transportation

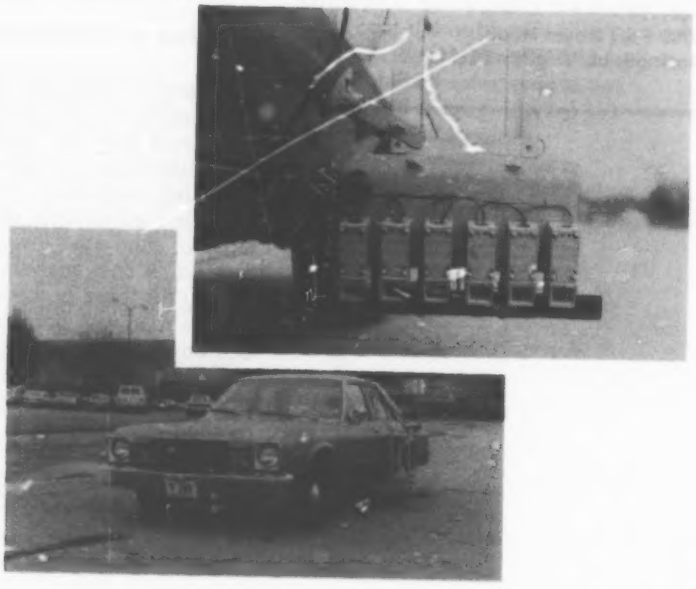
The Ohio Department of Transportation (ODOT) has built a device—LIFE-LITE—that can check for the presence of adequately-performing reflectors in snowplowable, raised pavement markers (SRPM's) at highway speeds.

The LIFE-LITE checker is a combination of two sensing systems. To detect the passage of the metal SRPM casting, ODOT adapted the antenna and associated circuitry from their Paint-Skip machine, an attachment for traffic paint stripers that interrupts paint flow across each SRPM in its path.

The optical system, which responds to the SRPM's retroreflector, consists of a row of six infrared scanners, off-the-shelf components that are common in the industrial control field. The scanners emit a pulsed, infrared light beam, and sense, with synchronous detection circuitry, a returned portion of that beam from a retroreflector—in this case, the one in the SRPM. The scanners respond within a millisecond by producing a voltage level change (essentially a switch closure) when their detection threshold is exceeded. They can operate as well in daylight as they can at night.

The sensors are mounted on a simple rectangular aluminum frame attached to the driver's side of the car. The metal-sensing antenna, which must have a small road clearance, is on a pivot so that it can deflect upward in case of contact with obstacles.

For more information on the LIFE-LITE, contact Mr. Wallace Richardson at the Ohio Department of Transportation, Bureau of Traffic, Research and Development Section, 25 S. Front Street, Columbus, OH 43215. Telephone: (614) 462-8175.



Guidelines for Slope Maintenance and Slide Restoration, Report No. FHWA-TS-85-231

by Office of Implementation

As part of a continuing project to evaluate and improve maintenance activities, a study on slope maintenance and slide restoration was undertaken. Slope maintenance and slide restoration was identified by a number of States as a major problem involving considerable maintenance funds.

This report discusses guidelines on slide identification and definition of terms, investigation and inspection of critical slopes and drainage, maintenance activities that will aid in the prevention and minimization of slides, maintenance activities that are related to particular distress items, and repair and restoration techniques including relative cost information.

The guidelines reflect the collective experience of the six participating States and are designed for use by the first level maintenance supervisor—the person responsible for scheduling day-to-day maintenance work.

The report may be purchased from NTIS (PB No. 86 245578).

Design and Construction of the Linn Cove Viaduct, Report No. FHWA-TS-84-214

by Office of Implementation

The Linn Cove Viaduct is located on the eastern slope of Grandfather Mountain in Avery County, North Carolina, in the last section of roadway to be completed along the Blue Ridge Parkway. This report documents the design and construction of the structure with indepth discussions on the major innovations in precast concrete segmental design, materials requirements, precasting, and erection procedures that were used in the project. The investigation, design, and construction of the structure's complex foundation requirements also are documented.

The progressive placement technique was used to construct the Linn Cove Viaduct to minimize the environmental impact on the site. Construction of the 1,243-ft (379-m) long structure with its S-and-one-half curvature proceeded overhead without the need for ground access except at the piers.

The report may be purchased from NTIS (PB No. 86 181682).

New Research in Progress

The following new research studies reported by FHWA's Offices of Research, Development, and Technology are sponsored in whole or in part with Federal highway funds. For further details on a particular study, please note the kind of study at the end of each description and contact the following: Staff and administrative contract research—*Public Roads* magazine; Highway Planning and Research (HP&R)—performing State highway or transportation department; National Cooperative Highway Research Program (NCHRP)—Program Director, National Cooperative Highway Research Program, Transportation Research Board, 2101 Constitution Avenue, NW., Washington, DC 20418.

FCP Category 1—Highway Design and Operation for Safety

FCP Project 1A: Traffic and Safety Control Devices

Title: Construction Costs and Safety Impacts of Work Zone Traffic Control Strategies. (FCP No. 31A5754)
Objective: Determine the costs and safety impacts associated with traffic control through work zones on four-lane divided highways using single-lane closure or two-lane, two-way traffic operations. Prepare an informational guide to assist highway engineers in selecting the most cost-effective traffic control strategy in rebuilding an existing rural, four-lane divided highway.
Performing Organization: E.N. Burns and Associates, Columbus, OH 43229
Expected Completion Date: September 1988
Estimated Cost: $248,660 (FHWA Administrative Contract)

FCP Project 1K: Accident and Countermeasure Analysis

Title: Trends in Highway Information. (FCP No. 31K1012)
Objective: Assess the impact of trends related to highway information on the ability of FHWA, States, and local jurisdictions to perform the highway safety mission successfully. Make recommendations concerning the appropriate means for dealing with reduced reporting of property-damage-only accidents and the process for identifying high-hazard locations and evaluating accident countermeasures.
Performing Organization: Daniel Consultants, Inc., Columbia, MD 21045
Expected Completion Date: June 1987
Estimated Cost: $105,725 (FHWA Administrative Contract)

FCP Project 1Z: Implementation of Safety R&D

Title: Accessible Networks for Elderly and Handicapped Pedestrians—Manual Revisions. (FCP No. 31ZN038)
Objective: Develop an updated manual to summarize current problems, opportunities for improvement, and beneficial changes to the existing priority accessible network procedure.
Performing Organization: KRW, Inc., Burke, VA 22015
Expected Completion Date: August 1987
Estimated Cost: $72,000 (FHWA Administrative Contract)

FCP Category 2—Traffic Control and Management

FCP Project 2P: Urban Freeway Management

Title: Investigation of Successful Communications and Traffic Control System Design, Installation, and Operations Practices. (FCP No. 32P2182)
Objective: Visit nine existing traffic control systems (including both freeway surveillance and control and signal systems) and perform indepth case studies of practices that resulted in successful design, installation, and operation of such systems. Develop guidelines for successful traffic control system implementation. Assess existing and new communications technologies used, or with potential for use, in traffic control systems including cable television, fiber optics, low-cost satellite communications, FM side-band communications, low-cost/low power UHF radio communications, and cellular telephone communications.
Performing Organization: JHK and Associates, Alexandria, VA 22304
Expected Completion Date: June 1988
Estimated Cost: $220,825 (FHWA Administrative Contract)

FCP Category 3—Highway Operations

FCP Project 3B: Environmental Management

Title: Determination of Noise Source Height of Vehicles on Florida Roads and Highways. (FCP No. 43B2026)
Objective: Apply source localization techniques used in Europe to identify noise sources to highway vehicle source heights to improve criteria for highway noise barriers. Use a seven-element microphone array and seven-channel tape recorders to measure noise of passing vehicles. Analyze noise signals. Measure source heights of individual vehicles on isolated roads, three roads with various kinds of truck traffic, and typical highways with heavy traffic. Develop source heights for vehicle type, speed, and sound frequency.
Performing Organization: Florida Atlantic University, Boca Raton, FL 33431
Funding Agency: Florida Department of Transportation
Expected Completion Date: June 1988
Estimated Cost: $132,110 (HP&R)

Title: Slope Erosion Control Study. (FCP No. 43B3232)
Objective: Characterize soil, granite, and other rocks for erosion resistance, weathering, and slope protection. Develop temporary and permanent slope protection systems. Evaluate literature and observations of roadside erosion control measures. Analyze the causes of and damage from erosion on road slopes and costs to drainage systems and traffic flows. Analyze in the laboratory soils and rocks representing those found on road slopes to determine the erosion indices with simulated weathering, soils tests, and artificial rainfall. Make field observations at 50 sites with various materials and treatments to determine soil erosion, plant behavior, and other conditions. Develop a manual for recommended practices to control roadside slope erosion.
Performing Organization: Arizona State University, Temple, AZ 85281
Funding Agency: Arizona Department of Transportation
Expected Completion Date: September 1987
Estimated Cost: $104,555 (HP&R)

Title: Construction Erosion Control. (FCP No. 43B3252)
Objective: Evaluate the effectiveness and costs of alternative means for erosion/pollution control at highway construction sites. Determine the most cost-effective measures and marginal costs for selection of more effective measures. Develop a highway construction site erosion/pollution control manual that presents decision criteria for strategy planning and guidelines and specifications for design and operation of control measures.
Performing Organization: University of Washington, Seattle, WA 98501
Funding Agency: Washington State Department of Transportation
Expected Completion Date: July 1987
Estimated Cost: $41,605 (HP&R)

FCP Category 4—Pavement Design, Construction, and Management

FCP Project 4C: Design and Rehabilitation of Flexible Pavements

Title: Development of an Improved Overlay Design Method. (FCP No. 44C1323)
Objective: Evaluate existing methods of overlay designs, both empirical and mechanistic, as well as the method used by Alaska. Develop an improved framework for overlay design. Collect data on selected projects including modulus and deflection, and test the developed system. Computerize the procedure.
Performing Organization: Oregon State University, Corvallis, OR 97331
Funding Agency: Oregon Department of Transportation
Expected Completion Date: April 1988
Estimated Cost: $27,750 (HP&R)

Title: Evaluation of Antistripping Additives. (FCP No. 44C4394)
Objective: Study in the field and laboratory five antistripping additives, including hydrated lime and four liquid chemical additives. Evaluate the additives with both a tensile strength test and a boiling water test.
Performing Organization: Virginia Highway Research Council, Charlottesville, VA 22903
Funding Agency: Virginia Department of Highways and Transportation
Expected Completion Date: June 1989
Estimated Cost: $28,000 (HP&R)

Title: Polymer Modified Asphalt Guidelines--Phase 1. (FCP No. 44C5114)
Objective: Develop guidelines for evaluating the performance of polymer modified aphalts in the laboratory. Use the guidelines to prepare preliminary specifications for purchasing such materials.
Performing Organization: New Mexico Engineering Research Institute, Albuquerque, NM 87131
Funding Agency: New Mexico State Highway Department
Expected Completion Date: October 1987
Estimated Cost: $82,000 (HP&R)

Title: Evaluation of Asphaltic Concrete Modifiers to Reduce Rutting. (FCP No. 44C5125)
Objective: Evaluate the effectiveness of asphalt additives to decrease rutting using three experimental pavement test sections—a control, a section containing the modified binder, and sections containing both modified and unmodified binders where a greater proportion of local, lower quality aggregate is used.
Performing Organization: Georgia Department of Transportation, Atlanta, GA 30334
Expected Completion Date: June 1989
Estimated Cost: $40,000 (HP&R)

Title: A Comparative Study of Performance of Different Designs for Flexible Pavements. (FCP No. 44C6344)
Objective: Collect data on material properties (moduli, permanent deformation parameters, etc.) for use in mechanistic design methods. Develop a mechanistic pavement performance predictive model. Compare the field performance of a pavement with the predicted performance. Evaluate the effect of different kinds and thicknesses of pavement layers on pavement distress and performance. Evaluate the effect of subgrade strength on the relative strength of each base course type.
Performing Organization: North Carolina State University, Raleigh, NC 27695
Funding Agency: North Carolina Department of Transportation
Expected Completion Date: December 1996
Estimated Cost: $50,000 (HP&R)

FCP Category 5—Structural Design and Hydraulics

FCP Project 5A: Bridge Loading and Design Criteria

Title: Computer-Aided Bridge Design/Drafting Integration—Phase I. (FCP No. 45A4142)
Objective: Integrate bridge design capabilities into the existing New Mexico State Highway Department computer-aided design/drafting (CADD) system. Develop the software necessary to interface the CADD system with the proposed AASHTO bridge design system as well as other design processes.
Performing Organization: New Mexico State University, Las Cruces, NM 88003
Funding Agency: New Mexico State Highway Department
Expected Completion Date: July 1987
Estimated Cost: $98,000 (HP&R)

FCP Project 5H: Highway Drainage and Flood Protection

Title: Estimating Flood Hydrographs and Volumes for Alabama Streams. (FCP No. 45H2622)
Objective: Develop a technique to estimate the shape of the average flood hydrograph and the flood volume from a given flood peak of a specific recurrence interval on ungauged basins with drainage areas of specified square miles with minimum in-channel storage.
Performing Organization: United States Geological Survey, Alabama District Office, Tuscaloosa, AL 35401
Funding Agency: Alabama Highway Department
Expected Completion Date: May 1988
Estimated Cost: $35,000 (HP&R)

Title: Development of a Risk-Cost Methodology to Size Detour Drainage Structures. (FCP No. 45H4952)
Objective: Establish a logic methodology capable of determining the design flood for a detour drainage on the basis of risk-cost relative to the permanent structure.
Performing Organization: University of Colorado, Boulder, CO 80309
Funding Agency: Colorado Department of Highways
Expected Completion Date: June 1987
Estimated Cost: $5,000 (HP&R)

FCP Project 5K: Bridge Rehabilitation Technology

Title: Long-Term Weathered Steel Beams. (FCP No. 45K2382)
Objective: Determine the loss in fatigue life of weathered steel beams after an equivalent of 25 years of exposure. Compare the results with existing data on nonweathered specimens tested under constant and variable amplitude fatigue, 2-year and 3-year weathered specimens, and the AASHTO fatigue specification requirements to determine the safe life expectancy of long-term weathered steel beams. Extrapolate the results to estimate expected loss in life at 50 years of service.
Performing Organization: University of Maryland, College Park, MD 20742
Funding Agency: Maryland State Highway Administration
Expected Completion Date: June 1987
Estimated Cost: $67,175 (HP&R)

Title: Field Monitoring of the Cable-Stayed, Segmental James River Bridge During Construction. (FCP No. 45K2402)
Objective: Instrument the I-295 James River cable-stayed bridge to determine live load stress range in the stay cables and the torsional and thermal stresses in the box girders. Evaluate the structural behavior of the delta frame assemblies, and evaluate the influence of concrete creep and shrinkage on the behavior of the bridge.
Performing Organization: Virginia Highway Research Council, Charlottesville, VA 22903
Funding Agency: Virginia Department of Highways and Transportation
Expected Completion Date: June 1989
Estimated Cost: $87,000 (HP&R)

FCP Project 5Q: Bridge Maintenance and Corrosion Protection

Title: Conductive Polymer Concrete Overlays. (FCP No. 35Q2642)
Objective: Install overlays having adequate conductance and good riding characteristics on deteriorated bridge decks. Evaluate the performance of these overlays for cathodic protection application to stop corrosion.
Performing Organization: Brookhaven National Laboratory, Upton, NY 11973
Expected Completion Date: September 1989
Estimated Cost: $244,960 (FHWA Administrative Contract)

FCP Category 9—R&D Management and Coordination

FCP Project 9D: Feasibility of New Technology for Highway Safety

Title: Basic Study to Improve Speed and Efficiency of Vehicle/Barrier Simulation. (FCP No. 39D6461)
Objective: Review available numerical analysis and nonlinear finite element methods to identify those methods that can improve the speed and efficiency of digital simulation of vehicle/barrier collisions. Study the technical and economic feasibility of incorporating these methods into FHWA's existing simulation programs. Study the feasibility of acquiring other appropriate simulation programs and installing them in FHWA's roadside safety library. Modify and improve these programs as necessary, and validate them against full-scale test data.
Performing Organization: Chiapetta, Welch and Associates, Inc., Palos Hills, IL 60465
Expected Completion Date: December 1988
Estimated Cost: $152,325 (FHWA Administrative Contract)

☆U.S. Government Printing Office: 1986—181-780/60001

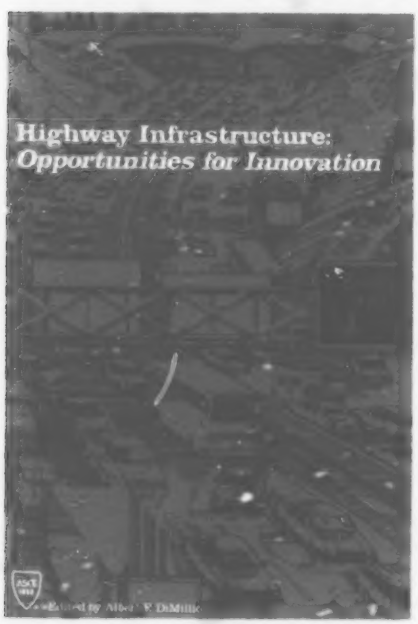
RD&T Outstanding Paper Awards Presented

Mr. Thomas J. Pasko, Jr., Dr. Yash Paul Virmani, Mr. Walter R. Jones, and Dr. Truman M. Mast were the recipients of the awards in the annual outstanding technical achievement competition held among the employees of the Federal Highway Administration's (FHWA) Offices of Research, Development, and Technology. The award covers the documentation of any technical accomplishment, which may be a publication, technical paper, report, film, or package; an innovative engineering concept; an instrumentation system; test procedure; new specification; mathematical model; or unique computer program. Each eligible candidate is judged on excellence, creativity, and contribution to the highway community, general public, and FHWA.

Mr. Pasko, Chief of the Pavements Division, Office of Engineering and Highway Operations Research and Development, Dr. Virmani, a research chemist in the Structures Division in the Office of Engineering and Highway Operations R&D, and Mr. Jones, a senior technician in the Structures Division, received awards for their research report "Polymer Concrete Used in Redecking a Major Bridge." This report, FHWA/RD-85/079, describes the successful use of polymer concrete for supporting the precast deck elements on the existing girders and stringers on the Woodrow Wilson Bridge, which crosses the Potomac River between Virginia and Maryland. The report may be purchased from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161 (PB No. 85 249290).

Dr. Mast, a research psychologist in the Traffic Systems Division, Office of Safety and Traffic Operations Research and Development, received an award for the research report "Motorist Direction-Finding Aids: Recovery From Freeway Exiting Errors," which he coauthored with Mr. William Lareau, Jr., who was on assignment with FHWA. The report, FHWA/RD-82/098, describes the results of a study that examined driver performance in a route-following situation using different kinds of direction-finding aids. The findings indicate that a significant motorist direction-finding problem exists and that different kinds of direction-finding aids can significantly increase motorist route-following efficiency. The report may be purchased from NTIS (PB No. 86 226206).

New Publication



The proceedings of a July 1985 conference held in Leesburg, Virginia, and sponsored by the Highway Division of the American Society of Civil Engineers and the Federal Highway Administration are contained in the report **Highway Infrastructure: Opportunities for Innovation.**

The 2-day conference focused on opportunities for highway innovation through research to develop methods to design, construct, and maintain the highway infrastructure in the most economical manner. The conference hoped to focus national attention on research as an effective and economical tool to help solve the Nation's highway infrastructure problems.

After opening remarks, a welcome, and the keynote address, the proceedings contain papers on the elements of innovation, the elements of a successful research and development program, and research success stories. The challenge facing the highway research community is addressed as well as the resources available to meet this challenge.

The report may be purchased for $15 (ASCE member, $11.25) from the American Society of Civil Engineers, 345 East 47th Street, New York, New York 10017-2398. (Book code #540.)

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The Arterial Analysis Package

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